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Airline Investment in Exclusive Airport Facilities - Timing Decisions under Demand Ambiguity

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Abstract: This paper studies the timing decision of airline investment in exclusive airport facilities in the presence of demand ambiguity and competition. We model the investment decision as a real options problem under ambiguity. The Multiple Prior Expected Utility form is used to describe the ambiguity-averse airline's preference. We obtain the optimal investment timing rule for the airline, which requires the airline's expected present value of the future profit increment to exceed its investment cost by the option value multipliers. Moreover, we compare the airline's investment timing to the social optimum and discuss two possible subsidy policies (a lump-sum subsidy and a per-unit subsidy) with which a government can align the airline's investment timing to the social optimum. We characterize a stepwise structure in both subsidy policies, in which the regulated ET investment timing depends on the comparisons of three thresholds: the social optimum, the airline's break-even timing, and the mixed timing between the social optimum and the airline optimum (i.e., profit maximization). Moreover, we conclude that the two subsidy policies have equivalent effects, leading to the same regulated ET timing and requiring the same amount of government funds, if the two parties have the same ambiguity levels.

Keywords: Airport investment; Investment timing; Knightian uncertainty; Real options; Vertical arrangements, Multiple Prior Expected Utility (MEU)

1. Introduction

In the aviation industry, airlines and airports may enter into various vertical arrangements. Airlines can therfore have varying degrees of control of airport facilities to secure exclusive or priority use (e.g., Barbot 2009, 2011; Fu and Zhang 2010; Fu et al. 2011). For example, Terminal 2 at Munich Airport is a joint investment by the airport (60%) and Lufthansa (40%). The terminal is specially designed to facilitate the operation of Lufthansa and its alliance airlines. At Frankfurt airport, a concourse named Flugsteig A-Plus is used solely by Lufthansa and its alliance partners. In the last round of major upgrades to Los Angeles International Airport, Southwest, American, Delta, and United invested in various projects, valued at US$400 million, US$33 million, US$229 million, and US$412 million, respectively (Xiao et al. 2016).

In other cases, exclusive use may be awarded by long-term contract instead of direct vertical investment. For example, Qantas and Sydney Airport signed a 30-year exclusive lease agreement on the airport's Terminal 3 in 1989.[1] Such practices are not limited to full-service airlines. Jazeera Airways, a Kuwait-based low-cost carrier, recently constructed a dedicated terminal at Kuwait International Airport (T5) at a cost of USD 50 million. Other examples include Bangkok Airways, the Thai regional airline that built and manages its own airports at Samui, Sukhothai, and Trat, and China United Airlines, a small commercial airline based at Beijing Nanyuan Airport, an ex-military base. These airlines operate the facilities themselves, process their passengers, and plan stands for their planes. In the case of cargo airlines, FedEx owns a control tower in the Guangzhou Baiyun airport in addition to dedicated aircraft parking spaces and cargo facilities.

Despite of the fact that airlines' vertical investments in airports are common across the globe, few studies have investigated the specifics of such decision. This paper analytically investigates an airline's timing decision for its vertical investment in airport facilities, modeled as an exclusive terminal (ET). Demand ambiguity (detailed definition in Section 3) and airline competition are explicitly considered. ETs are critical to airlines with benefits such as greater flexibility, better service quality, increased efficiency, and competitive advantages. Although ETs offer airlines many benefits, there are substantial costs and risks to construct and operate ETs. The construction of ETs requires a substantial investment, which is at least partially irreversible and sunk cost for airlines. The future benefits from ETs are uncertain and ambiguous because of demand uncertainty and competition from other airlines. All these factors make ET investment important but difficult to manage. Notably, because of the dynamic uncertainty of demand, an airline must manage a tradeoff: invest immediately or wait for better opportunities.

Therefore, studying the investment timing decision in ETs is a critical and practical topic for airlines. Specifically, our study addresses the following research questions: (1) In the context of demand ambiguity, how does an airline determine the timing of vertical investment? How would investor types, notably, ambiguity-averse versus ambiguity-loving behavior, influence investment timing decisions? (2) Compared with the socially optimal level, is the airline's vertical investment timing too early or too late? If the airline's investment timing deviates from the social optimum, can a government use regulatory tools, for

[1] In 2015, Qantas agreed to terminate the contract in exchange for A$535 million. The airline retains exclusive use of the terminal until June, 30, 2019, after which priority use is retained until 2025.

example, a subsidy, to align the airline's decision with the socially optimal outcome?

In addition to providing valuable insights into the business decisions in the aviation industry, our study makes several contributions to transportation literature :

(1) We analytically investigate airlines' investment timing decisions in a vertical structure under demand ambiguity. Specifically, we incorporate the dynamic ambiguity, flexible investment decision, and competition into our model to analyze infrastructure investment in the aviation industry. A few studies have investigated transportation investment under ambiguity (Section 2). However, they have not considered these issues simultaneously. Correspondingly, we examine the interaction of demand ambiguity, market competition, and vertical investment timing. The investor (the airline) in our study has no monopoly power and faces competition pressure[2] from other airlines. This is a critical feature, as much of the transportation industry cannot be characterized as a monopoly (e.g., Borenstein, 1992; Morrison and Winston, 1995; Heaver, 1995; Pels et al., 2000; Heaver et al., 2001; Brueckner et al. 2013; Lau et al. 2013; 2017; Jiang et al., 2017; Hasheminia and Jiang, 2017). The introduction of competition makes our analysis closer to reality and provides fresh management insights.

(2) We explore a government's regulations on airline's ET investment behavior when the two parties have different ambiguity levels. The ET investment regulation is specified as a call option exercised by the government in the presence of the airline's participation constraint and the non-negative subsidy constraint. We discuss two possible subsidy policies, that is, a lump-sum subsidy and a per-unit subsidy. Next, we characterize the stepwise structure in both subsidy policies, in which the regulated ET investment timing depends on the comparisons of three thresholds: the social optimum, the airline's break-even timing, and the mixed timing between the social optimum and the airline optimum (i.e., profit maximization). We observed that a larger shadow cost of public funds (subsidy) delays the regulated ET timing. Moreover, we conclude that the two subsidy policies have equivalent effects, leading to the same regulated ET timing and requiring the same amount of government funds, if the two parties have the same ambiguity levels. These findings methodologically add incremental contributions to the literature of real option analysis.

The remainder of this paper is organized as follows. Section 2 reviews the literature, and Section 3 investigates the investment timing decision from the perspectives of the airline and the social optimum when investors (airline/government) are ambiguity-averse. Section 4 examines the case where investors are ambiguity-loving. The last section concludes the paper with a discussion regarding policy implications and identifies areas for further investigation.

2. Literature Review

Three strands of literature are broadly related to this study: airport investment, transportation investment decisions under ambiguity, and real options.

The literature on airport investment has been well developed and considers features in the aviation industry such as lumpy investments, congestion, vertical structures, and commercial revenues (e.g., Oum

[2] This point also applies to the comparison of our paper with Nishimura and Ozaki (2007). The detailed comparison is made in Section 2.

and Zhang 1990; Zhang and Zhang 2003, 2006, 2010; Basso 2008; Zhang and Czerny 2012; Wan et al. 2015; Lin and Zhang 2017). However, the explicit modeling of the effects of uncertainty is relatively recent. Xiao et al. (2013) analyze the effects of demand uncertainty on airport capacity choices. Xiao et al. (2017) further use real option theory to study the uncertainty in airport investment. The most relevant work to ours is Xiao et al. (2016), which investigates the effects of airport-airline vertical arrangements on airport capacity choices under demand uncertainty.

Two distinctions are notable between this paper and Xiao et al. (2016). First, studies including Xiao et al. (2016) have derived analytical solutions when uncertainty can be characterized by a particular form of distribution, such as uniform or binomial distribution. By contrast, our model considers the ambiguity or Knightian uncertainty, which is more general and less restrictive. Second, our model is novel in that it explicitly considers the case of vertical investments on exclusive airport facilities (i.e., an ET); thus that service quality is endogenously chosen and can differ across airlines. This approach better captures market reality and enables us to explain business decisions observed in the aviation industry.

The studies on transportation investment and planning have been well developed but few have modeled ambiguity. Gao and Driouchi (2013) investigate rail transit investment under ambiguity. Wang and Zhang (2018) investigate disaster adaptation investments under ambiguity. As discussed, they have not considered the possibility of postponing the investment (i.e., investment timing), and the market structures modeled differ from those in the aviation industry. Balliauw et al. (2019) use a real option approach to explore the capacity investment decisions of two competing ports under uncertainty. Randrianarisoa and Zhang (2019) investigate the effect of port investment on the adaptation to climate change under competition. Although both have considered the postponing investment strategy, they do not consider the ambiguity in their framework. Therefore, our proposed model provides valuable complements to the literature.

Studies on real option analysis (ROA) are abundant, with classic books and survey papers dedicated to this important topic. See, for example, Dixit and Pindyck (1994), Azevedo and Paxson (2014), and Trigeorgis and Tsekrekosd (2018). Although we use a similar ROA method in an ET investment problem, our models address government regulation on an airline's investment behavior in an ambiguity setting and compare two subsidy policies, which provides new insights. Specifically, we compare our paper and that from Nishimura and Ozaki (2007). Nishimura and Ozaki (2007) are the first to apply the Chen and Epstein (2002) model to an irreversible investment problem. By contrast, we extend this application to a new setting where competition and the coexistence of exclusive and non-exclusive investments are considered. In particular, in Nishimura and Ozaki (2007), the decision maker is a monopoly evaluating an investment opportunity with a reference return of zero (i.e., the decision of not investing leads to a profit of zero). By contrast, we consider a decision maker (an airline) in competition with others, and not investing in an ET will not lead to zero return (the airline would continue to operate out of the common terminal but in a changed competition scenario).

These two differences make our paper fit reality better and have been demonstrated to have significant implications for analytical results. For example, the economics literature has illustrated that competition leads to different investment decisions (e.g., Tirole, 1988). Although the coexistence of exclusive and shared infrastructure has been less studied, some articles have pointed out its implications on infrastructure investment (e.g., Kaselimi et al., 2011). Moreover, we investigate the effect of government regulations (i.e., two subsidy policies) on an airline's investment, which, according to our review of the literature, has never been discussed in research that has applied Knightian uncertainty. In particular, (i) we transfer the government's regulations on the ET construction under demand ambiguity into a programming problem with a call option exercised by the government subject to the airline's participation constraint. (ii) We discuss two possible subsidy policies, namely, a lump-sum subsidy and a per-unit subsidy, and their applications in the government's regulation on the airline's ET investment.

We obtain one similar conclusion as those in the studies mentioned above: ambiguity delays the investment. However, we obtain more specific conclusions under our setting as follows: (i) An increase in the public terminal (PT) charge promotes an airline's ET investment; (ii) A government should prefer an earlier investment compared with the airline if they have the same ambiguity levels, and the competition between the airlines is not very intensive, or the PT charge is not very high; and (iii) We characterize the stepwise structures for these two subsidy policies and demonstrate their relationship: if a government and an airline have the same ambiguity levels, the two subsidy policies have equivalent effects, leading to the same regulated ET timing and requiring the same amount of funds from a government.

3. Vertical Airport Investment Under Ambiguity

In this section, we first present the basic framework of our models and the formulation of ambiguity, followed by the analysis of privately optimal and socially optimal ET investment decisions. Next, we compare market outcomes under these decisions. Finally, we discuss government regulations to align the airline's ET investment timing with the social optimum.

3.1 Model basics

First, we describe the demand system as follows. Two airlines, 1 and 2, offer differentiated and substitutable services in one airport. To improve service quality, Airline 1 plans to build an airport terminal that it would use exclusively. Additionally, Airlines 1 and 2 can use the PT in the airport. This case resembles a case at London Heathrow airport. The newest and most modern Terminal 5 is used by British Airways and Iberia, both operate under the IAG group. British Airways invested £330 million in this terminal (British Airways 2015), which opened in 2008. Before the shutdown of Terminal 1 in 2015, British Airways also used that terminal, whereas many of its Oneworld Alliance members have been using Terminal 3. Notably, British Airlines has recently renovated its lounge in Terminal 3.

In the case of New York JFK airport, terminals were known by the primary airline using it until the early 1990s. Delta has exclusive use of Terminal 2 and is a major user of Terminal 4. The latter is managed by JFK International Air Terminal (IAT) LLC, which also hosts many other airlines' international flights. In the 6 years until 2015, Delta had invested US$ 2 billion in JFK and LaGuardia (Delta 2015) and started another US$ 4 billion terminal investment in LaGuardia in 2017 (Flightglobal 2017).

In general, an airline can invest in various airport facilities in addition to terminals, such as fuel farms, lounges, self-check–in counters, luggage systems, and cargo terminals. The investing airline and its alliance members may have exclusive, priority, or equal use of these facilities depending on the contracts with the airports. For the convenience of reference, without loss of generality, we simply refer to the case of an ET and a PT in this paper. Such a setting also ensures that our modeling results can be easily extended to other transportation sectors such as marine ports. We assume that the demand functions of the two airlines have the following linear forms:

$$p_{11} = 1 + v - q_{11} - b(q_{12} + q_2) \tag{1}$$

$$p_{12} = 1 - q_{12} - b(q_{11} + q_2) \tag{2}$$

$$p_2 = 1 - q_2 - b(q_{11} + q_{12}) \tag{3}$$

where p_{11} and p_{12} denote the average airfares of Airline 1's flights through the ET and the PT, respectively; p_2 denotes the fare of Airline 2's flights through the PT; q_{11} and q_{12} denote the outputs of Airline 1 through the ET and the PT, respectively; and q_2 denotes the output of Airline 2 through the PT. $b \in (0,1]$ measures the degree of substitution between the services provided by the two airlines, which also represents the competition intensity. The intercepts of the demand function, which present potential market sizes, are normalized to 1. Assuming that the ET can promote the investing airline's demand by v ($v > 0$), the new market potential increases to $1+v$ after the investment. Here the market expansion parameter v is a relative value corresponding to the market scale. In the demand functions (1)–(3), we normalize the market scale parameter to 1. After airline 1's ET construction, the market scale of Airline 1 through its ET is expanded by v% from the original level.

Airline 1's investment decision is modeled with a two-stage game. In Stage 1, Airline 1 determines whether and when to invest in its ET to maximize its profit. To make the problem tractable, the ET investment is assumed to be lumpy, which equals I. In Stage 2, because of the availability of the invested ET, the two airlines engage in Cournot competition. Airline 1 chooses its outputs through the ET and the PT, namely, q_{11} and q_{12}, to maximize its total profit. Airline 2 chooses its output through the PT, namely, q_2, to maximize its profit. The profit functions of the two airlines are presented as follows:

$$\pi_1 = p_{11}q_{11} + (p_{12} - f)q_{12} \tag{4}$$

$$\pi_2 = (p_2 - f)q_2 \tag{5}$$

where π_1 and π_2 are their profits, respectively, and f is the terminal charge of the PT. The operation costs of the two airlines are normalized to 0. It is worthy pointing out that the positive operation costs of the two airlines will have no substantial impacts on our main conclusions (see the discussisons in Appendix D).

We also investigate the investment decisions of the ET from a socially optimal perspective, where the government regulates the ET investment in Stage 1 to maximize social welfare. The consumer utility of air passengers are represented in Equation (6), and consumer surplus can be obtained by deducting airfares from their utility. Social welfare is calculated as the sum of the consumer surplus, the profits of the airlines, and the profit of the PT.

$$u(q_{11}, q_{12}, q_2) = (1+v)q_{11} + q_{12} + q_2 - (q_{11}^2 + q_{12}^2 + q_2^2 + 2bq_{11}q_{12} + 2bq_{12}q_2 + 2bq_{11}q_2)/2 \quad (6)$$

3.2 Expression of ambiguity

Ambiguity refers to decision problems in which the probability distribution over states of the world is unknown or uncertain (Curley and Yates, 1985). According to Ellsberg (1961), many factors (e.g., the nature of information concerning the relative likelihood of events; a quality depending on the amount, type, and reliability; the "unanimity" of information, and degree of "confidence" in an estimate of relative likelihood) can all cause uncertainty in the probability distribution over states. In other words, ambiguity may result from different perceptions among the decision makers due to their different attitudes, confidence, or information status. The difference in the decision makers' subjective measures on the probabilities of the events decides the ambiguity level.

In reality, firms may not have complete confidence in their perceived probability when evaluating a project (e.g., Xiao et al., 2013). In our paper, because the ET is a new project, the decision makers inside an airline may have different opinions of its prospects and impacts. One reason for the opinion difference is a lack of historical data regarding the project's impact on specific markets. Other reasons may include interacted factors that may potentially influence future demand, such as passenger preference, economic growth, airline competition, network development, and ground transportations. The same arguments apply to government decisions on ET construction timing. Therefore, a precise prediction of demand is difficult and is a feature represented by the demand expansion parameter v in our model. To incorporate demand ambiguity into the dynamic evolution of v, we model the demand expansion of the ET at time t, v_t, a stochastic process and follows the GBM as follows:

$$dv_t = \mu v_t dt + \sigma v_t dB_t \quad (7)$$

Here, uncertainty is represented by a filtered probability space (Ω, F_t, Q), where F_t is a standard filtration for the standard Brown motion $(B_t)_{t\geq 0}$ with respect to the probability measure Q. Moreover, $v_0 > 0$, dB_t is a Wiener process. μ and σ are the expected growth rate and the volatility of v_t, respectively. In addition, we assume that $\mu < r$ and $\sigma > 0$, where r is the riskless discount rate. To make sense of the ET project evaluation, we must assume $\mu < r$; otherwise, the expected value of the ET (either to Airline 1 or to the government) could become infinitely large as over time (i.e., infinitely). This assumption is standard in the literature of real options (e.g., Dixit and Pindyck 1994). To further describe demand uncertainty from the perspective of Knightian dimension, we let $P = \{Q^\theta \mid \theta = (\theta_t) \in \Theta\}$ be the sets of GBM that deviate from the original probability distribution Q, where Θ is the set of density generators representing the sources of ambiguity. Thus, v_t can be expanded into a set of equations where the demand ambiguity is introduced through a range of GBMs such that

$$dv_t = (\mu - \sigma\theta_t)v_t dt + \sigma v_t dB_t^\theta \quad (8)$$

where the density generators θ_t are restricted to the non-stochastic interval $\mathrm{K} = [-\kappa, \kappa]$ that could define the level of ambiguity, with a bigger κ representing more ambiguity. To distinguish the different ambiguity levels of Airline 1 and the government, we use κ_S and κ_G to indicate their ambiguity levels, respectively. Some real options studies (e.g., Moon 2010; Xu et al., 2012) have used the future profit flow to reflect market uncertainty. In our paper, demand uncertainty v_t is the source that finally leads to the uncertainties of an airline's profit and the future social welfare (v_t is in the airline's profit and the social welfare functions. The details are presented in the following discussions). Moreover, if the market price is constant (not related to the demand), the demand uncertainty equals to profit uncertainty. In our paper, because the price is related to demand, profit uncertainty is more complicated than demand uncertainty (the airline's profit is a quadratic function of v_t, and q_{11}, q_{12}, and q_2 are the linear functions of v_t). Therefore, our paper analyzes one of the possible sources of the uncertainty of the firm's future profit flow and can characterize industry reality well.

ETs can offer their investors many benefits, such as greater flexibility, reliability, short turnaround time, and increased efficiency. These benefits help airlines enhance their demand potential, reflected by the parameter v in Equation (1). Such demand expansion effect can be illustrated by the ET constructed by the Dubai based airline Emirates. After Emirates' ET (Terminal 3 of Dubai Airport) opened in October 2008, its average annual growth rate has increased since 2009 (Figure 1). This finding illustrates that an airline's demand can be promoted by its ET.

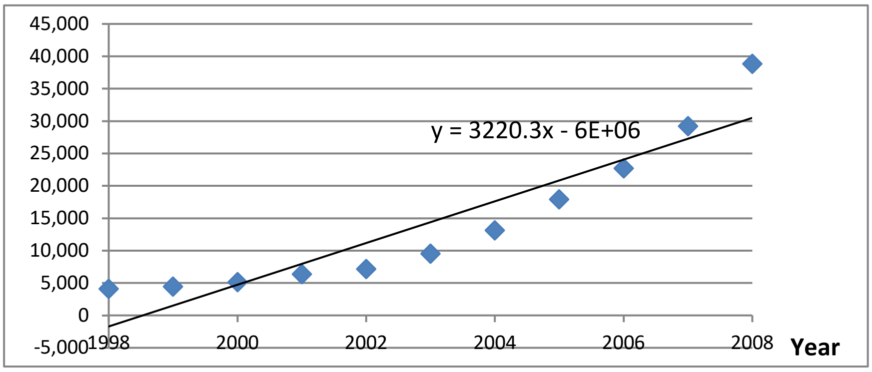

Figure 1-A The turnover increase of the Emirates before its ET use

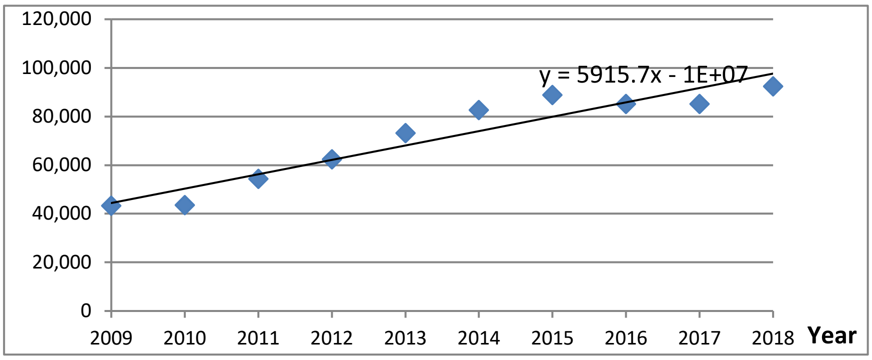

Figure 1-B The turnover increase of the Emirates after its ET use

In practice, we can use empirical methods (e.g., regression) to estimate the demand function before and after projects similar to ET construction based on historical data. The total difference of the slopes and the error terms of the demand functions before and after such projects can be used to estimate the expansion parameter. The approach proposed by Campbell et al. (1996) to estimate the parameters of GBMs is one such example. The detailed process is described as follows: (i) Normalize the total difference of the slopes and the error terms of the demand functions as v_t. (ii) Define $r_t = \log(v_t) - \log(v_{t-\Delta t})$, where *Δt* is the time interval of the sample. Denote $\bar{r}$ and s_r as the mean and standard deviation of the sample v_t, respectively. They can be expressed as follows: $\bar{r} = \frac{\sum_{t=1}^{T} r_t}{T}$, $s_r = \sqrt{\frac{\sum_{t=1}^{T}(r_t - \bar{r})^2}{T-1}}$, where *T* is the number of the sample. (iii) The estimation of the drift and the volatility of v_t, that is, μ and σ, can be obtained using the following formulas: $\hat{\sigma} = \frac{s_r}{2\Delta t}$ and $\hat{\mu} = \frac{r}{\Delta t} + \frac{\hat{\sigma}^2}{2}$. Important ambiguity parameters (κ_S and κ_G) can be obtained with questionnaires collected from professional experts. According to Schröder (2011), κ should satisfy constraint $\kappa < (r - \mu)/\sigma$, which can be used as the upper bound of κ_S and κ_G.

3.3 Analysis

3.3.1 Airline 1's single-period profit increment after ET construction

We first analyze airlines' output decisions in Stage 2. Substituting (1)–(3) into (4) and (5), we find that the equilibrium outputs of the two airlines in each period are as follows:

$$q_{11} = \frac{(2-b)[(2+b)v + 3bf - 2b + 2]}{4(1-b)(2+2b-b^2)} \tag{9}$$

$$q_{12} = \frac{b(b-4)v + (2-f)b^2 + (2f-6)b + 4 - 4f}{4(1-b)(2+2b-b^2)} \tag{10}$$

$$q_2 = \frac{-bv - (2+b)f + 2}{4 + 4b - 2b^2} \tag{11}$$

From (9) and (10) it can be observed that a demand expansion v increases Airline 1's outputs through the ET (q_{11}) and decreases the outputs though the PT (q_{12}). Therefore, Airline 1 reallocates outputs between its ET and the PT after ET construction. Substituting (9)–(11) into (4), we obtain Airline 1's single-period profit after ET construction. In Appendix A, we obtain Airline 1's single-period profit without ET. Therefore, its single-period profit increment after ET construction, or the difference between its single-period profit with and without ET, can be expressed as follows:

$$\Delta\pi_{1t} = \omega_{2S} v_t^2 + \omega_{1S} v_t + \omega_{0S} \tag{12}$$

where $\Delta\pi_{1t}$ is Airline 1's single-period profit increment, and

$\omega_{2S} = \frac{b^4 - 4b^3 - 4b^2 + 8b + 8}{8(1-b)(2+2b-b^2)^2}$, $\omega_{1S} = \frac{fb^4 + (4-8f)b^3 + (4f-8)b^2 + (12f-4)b + 8}{4(1-b)(2+2b-b^2)^2}$

$$\omega_{0S} = \frac{1}{8(1-b)(4+6b-b^3)^2}[(2-f)(3f-2)b^6 + (8-8f)b^5 - (36f^2-24f+4)b^4$$
$$+(48f^2-104f+32)b^3 + (72f^2-16f-32)b^2 + (96f-32)b + 32]$$

Here, the subscript "S" is used to denote Airline 1.

The denominator of ω_{2S} is positive. Differentiating the numerator of ω_{2S} twice with respect to b, we know that $(b^4-4b^3-4b^2+8b+8)'' = 12b^2-24b-8<0$ when $b\in(0,1)$. Thus, the numerator of ω_{2S} is a concave function with respect to b. Moreover, when $b=1$, the numerator of ω_{2S} is positive. When $b=0$, the numerator of ω_{2S} is positive too. Therefore, $\omega_{2S}>0$ when $b\in(0,1)$. This finding satisfies the condition that the profit flow should be a convex function of the stochastic variable (Dixit and Pindyck 1994, pp. 197). Judging the sign of ω_{1S} is also useful. Because of the complexity of ω_{1S}, an analytic investigation is difficult. Fortunately, the areas of the related parameters in ω_{1S} are limited because $b\in[0,1)$ and $f\in[0,1]$. With this finding, we can analyze ω_{1S} numerically, which suggests that $\omega_{1S}>0$ for all $b\in[0,1)$ and $f\in[0,1]$.

3.3.2 Investment decision preferred by Airline 1

From (12), it is clear that Airline 1's profit increment and ET investment are related to stochastic process v_t. With demand uncertainty, Airline 1 faces the tradeoff between making an investment immediately and waiting for better opportunities. In other words, Airline 1's investment decision is a real options investment problem. Many preference models incorporate ambiguity, for example, in the finance and economics literature (e.g., Klibanoff et al., 2005; Skiadas, 2014). Here, the Multiple Prior Expected Utility framework in continuous time (Chen and Epstein, 2002; Nishimura and Ozaki, 2007) is used to model the completely pessimistic airline and government in this section, because it is dynamic and consistent. Although it focuses exclusively on ambiguity-averse decision makers whose actions are based on the worst scenarios, it is reasonable for our analysis because ET construction has substantial sunk costs, and thus, investors are expected to be very cautious. To complete the analysis, we further analyze the case of completely optimistic investors in Section 4. Ambiguity-averse Airline 1's present value of the future profit increment can therefore be expressed as

$$\Pi_1 = \inf_{\theta\in \mathrm{K}} E^{Q^\theta}[\int_0^\infty e^{-rt}\Delta\pi_{1t}dt \mid F_t] \tag{13}$$

where Π_1 is Airline 1's expected present value of the future profit increment after ET construction at time 0. Proposition 1a provides the value of Π_1. Related proofs are provided in Appendix B.

Proposition 1a. *Let the level of ambiguity be specified by the set* $\mathrm{K}_S = [-\kappa_S, \kappa_S]$. *Next, given that the ambiguity-averse Airline 1's preference is (13) and the rectangular structure of beliefs* P, *its expected present value of the future profit increment after the ET construction is given by*

$$\Pi_1 = \Phi_{2S}\omega_{2S}v_0^2 + \Phi_{1S}\omega_{1S}v_0 + \frac{\omega_{0S}}{r} \tag{14}$$

where $\Phi_{2S} = \dfrac{1}{r-2(\mu-\kappa_S\sigma)-\sigma^2}$ *and* $\Phi_{1S} = \dfrac{1}{r-(\mu-\kappa_S\sigma)}$.

To interpret (14), we first consider the case without ambiguity, $\kappa_S = 0$. Next, (14) reduces to $\Pi_1 = \dfrac{1}{r-2\mu-\sigma^2}\omega_{2S}v_0^2 + \dfrac{1}{r-\mu}\omega_{1S}v_0 + \dfrac{\omega_{0S}}{r}$, which can be interpreted as the expected present value of Airline 1's profit increment stream π_{1t} calculated with the "risk-adjusted discount rate." According to Dixit and Pindyck (1994, pp. 197), the risk-adjusted discount rate is $r-\mu\eta-\frac{1}{2}\sigma^2\eta(\eta-1)$, where η is the power of the stochastic variable in the profit function. In Airline 1's profit increment function π_{1t}, the powers of the stochastic variable v are 2, 1, and 0 in the different terms, respectively. Thus, their corresponding risk-adjusted discount rates are $\dfrac{1}{r-2\mu-\sigma^2}$, $\dfrac{1}{r-\mu}$, and $\dfrac{1}{r}$ in the case without ambiguity, respectively. Now, in the case of complete ambiguity, the risk-adjusted discount rates are similar to the case without ambiguity except that the terms μ are replaced by $\mu-\kappa_S\sigma$, which are Φ_{2S}, Φ_{1S}, and $1/r$, respectively. In summary, Π_1 is the expected present value of Airline 1's profit increment calculated by the "risk-adjusted discount rate under ambiguity."

Next, we examine the impact of the ambiguity degree κ on Airline 1's expected present value of future profit increment Π_1. It is easy to show that $\partial\Phi_{2S}/\partial\kappa_S < 0$ and $\partial\Phi_{1S}/\partial\kappa_S < 0$. Because $\omega_{2S} > 0$, $\omega_{1S} > 0$, $\partial\omega_{2S}/\partial\kappa_S = 0$, $\partial\omega_{1S}/\partial\kappa_S = 0$, and $\partial\omega_{0S}/\partial\kappa_S = 0$, we have $\partial\Pi_1/\partial\kappa_S < 0$, which means that an increase in ambiguity has a negative impact on the expected present value of the Airline's future profit increment. We call this phenomenon the "present-value effect" of the ambiguity for the following reason. From (8), we know that the ambiguity has two possibly opposite effects on the demand expansion parameter v and Airline 1's expected present value of its future profit increment Π_1: a downside risk when $\theta_t < 0$ or an upside potential when $\theta_t > 0$. When Airline 1 is ambiguity-averse, only the worst case ($\theta_t = -\kappa_S$) is relevant. In other words, the airline focuses only on the downside risk and neglects the upside potential, which causes negative impacts of ambiguity on its prospect. Corollary 1a summarizes the result.

Corollary 1a. *Given that Airline 1 is completely ambiguity-averse, an increase in ambiguity* κ_S *has a negative impact on its expected present value of the future profit increment,* $\partial\Pi_1/\partial\kappa_S < 0$.

Now, we analyze Airline 1's investment decision in Stage 1 to maximize its option value under ambiguity. In other words, Airline 1 has the following optimal stopping problem:

$$V = \max_{\tau \geq 0}[\inf_{\theta \in [-\kappa_S, \kappa_S]} E^{Q^\theta}(\int_\tau^\infty e^{-rt} \Delta\pi_{1t} dt \mid F_t) - e^{-r\tau} I] \tag{15}$$

by choosing an (F_t)-stopping time, $\{\tau \geq 0\} \in F_t$, where V is the option value of the investment and τ is investment timing. Equation (15) means that Airline 1 attempts to determine the investment timing to maximize its net present value, which is the expected present value of the future profit increment minus the present value of ET investment. We solve (15) and obtain the investment rule preferred by Airline 1 as summarized in Proposition 1b.

Proposition 1b. *If $I \leq \omega_{0S} / r$, ambiguity-averse Airline 1 should make the ET investment immediately, $v_S = v_0$. Otherwise, its optimal ET investment timing, v_S, is the positive root of the following equation:*

$$\Phi_{2S}(1 - \frac{2}{\beta_S})\omega_{2S} v_S^2 + \Phi_{1S}(1 - \frac{1}{\beta_S})\omega_{1S} v_S + \frac{\omega_{0S}}{r} = I, \tag{16}$$

where $\beta_S = \frac{1}{2} - \frac{\gamma_S}{\sigma^2} + \sqrt{(\frac{\gamma_S}{\sigma^2} - \frac{1}{2})^2 + \frac{2r}{\sigma^2}} > 2$ and $\gamma_S = \mu - \kappa_S \sigma$.

Proposition 1b provides the optimal investment rule as follows: when the investment is low, $I \leq \omega_{0S} / r$, Airline 1's present value of the future profit increment is sufficiently large to cover the investment even without demand expansion (v_t=0).Airline 1 can make the investment immediately. When the investment is high, $I > \omega_{0S} / r$, Airline 1 should not make the investment until the demand expansion attains or exceeds the threshold v_S, that is, $v_t \geq v_S$. We interpreted this rule. In the LHS of (16), the term $1 - 2/\beta_S$ and $1 - 1/\beta_S$ are the inverses of the "option value multipliers." According to Dixit and Pindyck (1994), the option value multiplier is $\beta_S / (\beta_S - \eta)$, where η is the power of the stochastic variable in the single-period profit increment function. In Airline 1's single-period profit increment function π_{1t} (recall Equation [12]), the powers of the stochastic variable v are 2, 1, and 0, respectively. Therefore, the corresponding option value multipliers are $\beta_S / (\beta_S - 2)$, $\beta_S / (\beta_S - 1)$, and 1, respectively, and their inverses are $1 - 2/\beta_S$, $1 - 1/\beta_S$ and 1, respectively. We know that $\beta_S > 2$, which leads to $\beta_S / (\beta_S - 2)$ and $\beta_S / (\beta_S - 1)$. Their inverses are both less than 1. The whole LHS of (16) is the option value of the investment, which equals Airline 1's expected present value of the future profit increment descaled by the inverses of the option value multipliers. The right-hand side (RHS) of (16) is the ET investment. If $\kappa_S = 0$ and $\sigma = 0$, neither risk nor ambiguity exists; thus, $\beta_S \to \infty$ and (16) becomes $\frac{\omega_{2S} v_S^2}{r - 2\mu} + \frac{\omega_{1S} v_S}{r - \mu} + \frac{\omega_{0S}}{r} = I$. This finding indicates that under certainty, Airline 1 makes the investment when the present value of the future profit increment equals the investment cost. However, under risk and ambiguity, $\kappa_S \neq 0$ and $\sigma \neq 0$, and we have $\beta_S \neq \infty$. Because $1 - \frac{2}{\beta_S} < 1$ and $1 - \frac{1}{\beta_S} < 1$, Airline 1 makes the investment only if the expected present value of the future profit increment exceeds its investment cost. Because the option value multipliers are greater than (at least equal to) 1, the optimal investment rule (16) indicates that under ambiguity, Airline 1's expected present value of the future profit increment needs to exceed the investment cost by the option value multipliers. This result is consistent with the standard real options theory. Next, we investigate the impact of the ambiguity on the ET investment timing and post Corollary 1b.

Corollary 1b. *If Airline 1 is ambiguity-averse, its investment under ambiguity is always delayed compared with that under certainty,* $\partial v_S / \partial \kappa_S > 0$.

To interpret Corollary 1b, let $B_{2S} = 1 - \frac{2}{\beta_S}$, $X_{2S} = \Phi_{2S} B_{2S}$ and $B_{1S} = 1 - \frac{1}{\beta_S}$, $X_{1S} = \Phi_{1S} B_{1S}$. We have $\frac{\partial X_{2S}}{\partial \kappa} = \frac{\partial X_{2S}}{\partial \Phi_{2S}} \cdot \frac{\partial \Phi_{2S}}{\partial \kappa} + \frac{\partial X_{2S}}{\partial B_{2S}} \cdot \frac{\partial B_{2S}}{\partial \kappa}$ and $\frac{\partial X_{1S}}{\partial \kappa} = \frac{\partial X_{1S}}{\partial \Phi_{1S}} \cdot \frac{\partial \Phi_{1S}}{\partial \kappa} + \frac{\partial X_{1S}}{\partial B_{1S}} \cdot \frac{\partial B_{1S}}{\partial \kappa}$, that is, the impact of ambiguity to the investment can be reflected by the interaction of two effects: the "present-value effect" (through Φ_{2S} and Φ_{1S}) and the "option–value effect" (through B_{2S} and B_{1S}). From the proof in Appendix B, we know that $\frac{\partial X_{2S}}{\partial \Phi_{2S}} > 0$, $\frac{\partial \Phi_{2S}}{\partial \kappa} < 0$, $\frac{\partial X_{2S}}{\partial B_{2S}} > 0$, $\frac{\partial B_{2S}}{\partial \kappa} > 0$, and $\frac{\partial X_{1S}}{\partial \Phi_{1S}} > 0$, $\frac{\partial \Phi_{1S}}{\partial \kappa} < 0$, $\frac{\partial X_{1S}}{\partial B_{1S}} > 0$, $\frac{\partial B_{1S}}{\partial \kappa} > 0$. In other words, these two effects have the opposite directions to the investment. When the ambiguity increases, the present-value effect weakens, and the option–value effect strengthens. In the proof in Appendix B, the option–value effect dominates the present-value effect; thus, the investment is delayed.

We further investigate the airport/government's strategy to influence Airline 1's investment timing decision. In our model, the terminal charge of the PT, namely, f, can be used to achieve such an objective, and we use Corollary 1c to manifest this.

Corollary 1c. *Given Airline 1's ambiguity degree* κ_S*, an increase in the PT charge always promotes Airline 1's ET investment,* $\partial v_S / \partial f < 0$.

Corollary 1c leads to a possible policy for the government to influence Airline 1's investment behavior. Regarding the two airlines' output decisions, namely, (9)–(11) in Section 3.3.1, we easily observe that $\partial q_{11} / \partial f > 0$, $\partial q_{12} / \partial f < 0$, and $\partial q_2 / \partial f < 0$. A higher PT charge promotes ET output and restrains the PT output. q_{11} and q_{12} are Airline 1's profit sources. The impact of an increase in the PT charge to Airline 1's profit depends on the tradeoff between its impacts and outputs in the ET and the PT. When the PT charge increases, the decrease in profit from the PT is less than the increase in profit from the ET, leading to an increase in total profit. According to the optimal ET investment rule (16), Airline 1 invests in the ET earlier.

3.3.3 Social optimal ET investment decision

Now, we discuss the investment decision from the perspective of social optimum, which may correspond to the case when the investment decision is determined or influenced by a government/regulator that aims to maximize social welfare. This phenomenon may characterize the cases when an airport is publicly owned or under government regulation. Substituting (9)–(11) into the social welfare function (6), we obtain the single-period social welfare after ET construction. In Appendix A, we obtain single-period social welfare without ET. Therefore, the single-period social welfare increment with investment, or the difference of the single-period social welfare with and without ET can be expressed as follows:

$$\Delta u_t = \omega_{2G} v_t^2 + \omega_{1G} v_t + \omega_{0G} \tag{17}$$

where $\omega_{2G} = \dfrac{3b^4 - 10b^3 - 14b^2 + 24b + 24}{16(1-b)(2+2b-b^2)^2}$,

$$\omega_{1G} = \frac{(f-4)b^4 + (24-10f)b^3 + (2f-28)b^2 + (16f-16)b + 24}{8(1-b)(2+2b-b^2)^2},$$

$$\omega_{0G} = \frac{1}{16(1-b)(4+6b-b^3)^2}[(2-3f)(2+7f)b^6 + (42f^2 - 24f - 16)b^5 + (18f^2 + 112f - 52)b^4$$
$$-(96f^2 + 128f - 200)b^3 - (24f^2 + 96f + 104)b^2 + (128f - 128)b + 96]$$

Here, subscript "G" is used to denote the influence of government. The denominator of ω_{2G} is positive. By differentiating the numerator of ω_{2G} twice with respect to b, we know that $(3b^4 - 10b^3 - 14b^2 + 24b + 24)'' = 36b^2 - 60b - 28 < 0$ when $b \in (0,1)$. Thus, the numerator of ω_{2G} is a concave function with respect to b. Moreover, when $b = 1$, the numerator of ω_{2G} is positive. When $b = 0$, the numerator of ω_{2G} is positive too. Therefore, $\omega_{2G} > 0$ when $b \in (0,1)$. Moreover, we can numerically demonstrate that the numerator of ω_{1G}, i.e., $(f-4)b^4 + (24-10f)b^3 + (2f-28)b^2 + (16f-16)b + 24 > 0$ for all $b \in [0,1)$ and $f \in [0,1]$. Because the denominator of ω_{1G} is positive, we know that $\omega_{1G} > 0$ when $b \in [0,1)$ and $f \in [0,1]$.

Similar to Section 3.3.2, we define the present value of the future social welfare increment after the ET construction as follows:

$$U = \inf_{\theta \in \mathrm{K}} E^{Q^\theta}[\int_0^\infty e^{-rt} \Delta u_t dt \mid F_t] \tag{18}$$

Where U is the expected present value of the future social welfare increment at time 0. Similar to Section 3.3.2, we first consider the case in which the government is ambiguity-averse and then discuss the case of ambiguity-loving government in Section 4. Proposition 2a provides the value of U.

Proposition 2a. *Let the level of ambiguity be specified by the set* $\mathrm{K}_G = [-\kappa_G, \kappa_G]$. *Next, given the* *ambiguity-averse government's preference as (18) and the rectangular structure of beliefs P, the expected present value of the future social welfare increment is given by*

$$U = \Phi_{2G}\omega_{2G}v_0^2 + \Phi_{1G}\omega_{1G}v_0 + \frac{\omega_{0G}}{r} \tag{19}$$

where $\Phi_{2G} = \dfrac{1}{r - 2(\mu - \kappa_G\sigma) - \sigma^2}$ and $\Phi_{1G} = \dfrac{1}{r - (\mu - \kappa_G\sigma)}$.

We find a similar "present-value effect" of the ambiguity in the government's expected present value of the future social welfare increment. Because $\partial\omega_{2G} / \partial\kappa = 0$, $\partial\omega_{1G} / \partial\kappa = 0$, $\partial\omega_{0G} / \partial\kappa = 0$, $\omega_{2G} > 0$, and $\omega_{1G} > 0$, we have $\partial U / \partial\kappa_G < 0$; thus, an increase in ambiguity has a negative impact on the expected present value of the future social welfare increment.

When determining the investment timing, the government has the following optimal stopping problem:

$$W = \max_{\tau\ge 0}[\inf_{\theta\in[-\kappa_G,\kappa_G]} E^{Q^\theta}(\int_\tau^\infty e^{-rt}\Delta u_t dt \mid F_t) - e^{-r\tau}rI] \tag{20}$$

We apply a similar approach, and the socially optimal investment timing can be obtained as summarized in Proposition 2b.

Proposition 2b. *If $I \le \omega_{0G} / r$, a completely ambiguity-averse government should make the ET investment immediately, $v_G = v_0$. Otherwise, the optimal ET investment timing, v_G, is the positive root of Equation (21):*

$$\Phi_{2G}(1 - \frac{2}{\beta_G})\omega_{2G}v_G^2 + \Phi_{1G}(1 - \frac{1}{\beta_G})\omega_{1G}v_G + \frac{\omega_{0G}}{r} = I \tag{21}$$

where $\beta_G = \dfrac{1}{2} - \dfrac{\gamma_G}{\sigma^2} + \sqrt{(\dfrac{\gamma_G}{\sigma^2} - \dfrac{1}{2})^2 + \dfrac{2r}{\sigma^2}} > 2$ and $\gamma_G = \mu - \kappa_G\sigma$.

Equation (21) describes a similar structure of the government's investment rule: The optimal investment makes the government's expected present value of the future social welfare increment exceed investment cost by the option value multipliers. Similarly, we find the impact of the ambiguity on the government's investment timing choice as summarized in Corollary 2.

Corollary 2. *If a government is ambiguity-averse, the ET investment under ambiguity is always delayed compared with that under certainty, $\partial v_G / \partial\kappa_G > 0$.*

3.3.4 Comparisons of the ET investment decisions

Next, we compare the outcomes under different decision makers, that is, Airline 1 and the government. In Proposition 3, we show that the social optimal ET investment timing is not consistent with Airline 1's preferred timing in most cases, even when the government has the same ambiguity level as

Airline 1. This finding raises the necessity for regulation on Airline 1's investment behavior (see discussion in Section 3.3.5).

Proposition 3. *If the government has the same ambiguity level as Airline 1,* $\kappa_S = \kappa_G = \kappa$, *we have* $\Phi_{2S} = \Phi_{2G} = \Phi_2 = \dfrac{1}{r - 2(\mu - \kappa\sigma) - \sigma^2}$, $\Phi_{1S} = \Phi_{1G} = \Phi_1 = \dfrac{1}{r - (\mu - \kappa\sigma)}$, $\gamma_S = \gamma_G = \gamma = \mu - \kappa\sigma$, and $\beta_S = \beta_G = \beta = \dfrac{1}{2} - \dfrac{\gamma}{\sigma^2} + \sqrt{(\dfrac{\gamma}{\sigma^2} - \dfrac{1}{2})^2 + \dfrac{2r}{\sigma^2}}$. *We define the parameter areas with respect to b and f as follows:* $\Gamma_1 = \{0 \le b < \dfrac{2}{11}, 0 \le f \le 1\}$, $\Gamma_2 = \{\dfrac{2}{11} \le b \le \dfrac{2}{3}, 0 \le f \le \dfrac{4 - 10b + 6b^2}{14b - 5b^2}\}$, $\Gamma_3 = \{\dfrac{2}{11} \le b \le \dfrac{2}{3}, f \ge \dfrac{4 - 10b + 6b^2}{14b - 5b^2}\}$, *and* $\Gamma_4 = \{\dfrac{2}{3} \le b \le 1, 0 \le f \le 1\}$. *The following comparison results hold:*

(i) if $I \le \min(\dfrac{\omega_{0S}}{r}, \dfrac{\omega_{0G}}{r})$, *the ET investment timing decisions of Airline 1 and the government always coincide,* $v_S = v_G = v_0$;

(ii) if $I > \min(\dfrac{\omega_{0S}}{r}, \dfrac{\omega_{0G}}{r})$ *and* $(b, f) \in \Gamma_1 \cup \Gamma_2$, *Airline 1's preferred ET investment timing is always later than the social optimum,* $v_S > v_G$. *Moreover, the time difference increases as the ambiguity level increases,* $\partial(v_S - v_G)/\partial\kappa > 0$;

(iii) if $I > \min(\dfrac{\omega_{0S}}{r}, \dfrac{\omega_{0G}}{r})$ *and* $(b, f) \in \Gamma_3 \cup \Gamma_4$, *the comparison of the ET investment timing decisions between Airline 1 and the government is not certain.*

Based on Proposition 3, the following insights can be obtained:

(i) When the ET investment is very low (less than $\min(\dfrac{\omega_{0S}}{r}, \dfrac{\omega_{0G}}{r})$ in our model), the investment timing of the government is the same as that of Airline 1 (invest immediately).Regulation is not necessary.

(ii) When ET investment is not very low (larger than $\min(\dfrac{\omega_{0S}}{r}, \dfrac{\omega_{0G}}{r})$), whether ET investment timing decisions are the same depends on market competition and the PT charge. Consider the case in wihch both the government and Airline 1 are ambiguity-averse, and they have the same ambiguity levels. When the competition between the airlines is not very intensive, or the PT charge is not very high, the government prefers an earlier investment than that of Airline 1. Facing the same demand expansion opportunity v_t, the ET capacity preferred by the government is larger than that preferred by Airline 1 under the aforementioned prerequisite. (Based on the proof of Proposition 3, if $v_S = v_G$, the RHS of [16] must be less than the RHS of [21]; therefore, with the same v, $I_S < I_G$). This conclusion is consistent with the findings in the literature that profit-maximizing operators are inclined to underinvest in an airport compared with welfare-maximizing operators (Zhang and Zhang, 2006). Our conclusions extend the findings to dynamic and ambiguity scenarios. The reason is as follows. When airline competition is not sharp, Airline 1 has relatively higher market power. The difference between the objectives of the government (social welfare maximization) and Airline 1 (profit maximization) is more significant. The payoff difference from the ET investment is larger too. To achieve the broader objective (i.e., maximizing social welfare, comprising consumer surplus and both airlines' profits, rather than the profit of the investing Airline 1 only), the government must promote more investment, despite the future "investment revenues" being uncertain and ambiguous. When the competition between the airlines is more intense, the difference between the objectives of the government and Airline 1 narrows. For the sake of competition, Airline 1's payoff from ET construction may exceed that of the government. Thus, an airline may prefer an earlier investment than a government.

(iii) Although higher ambiguity delays the ET investment for the government and Airline 1, in the aforementioned scope (where the competition between airlines is not very intensive or the PT charge is not very high), increasing ambiguity has larger impacts on Airline 1's ET timing than that of the government. In other words, when the demand expansion becomes more ambiguous, Airline 1's ET timing is delayed further than the government's. The reason this phenomenon occurs is that their objective difference is enlarged as the ambiguity level increases (based on the proof of Proposition 5, differences between ω_{2G}, ω_{1G}, and ω_{0G} and ω_{2S}, ω_{1S}, and ω_{0S} enlarge as κ_G increases), causing Airline 1 to be more conservative regarding ET investment than the government.

One example that may testify our result is airBaltic's investment to build and operate a terminal in SJSC Riga International Airport, a government owned airport. The contract was initially offered to TAV Airports Holding, an airport operator based in Turkey, but was later canceled. The airport authority then offered a similar contract to airBaltic, Latvia's flag carrier and a dominant player in Riga Airport (with a market share above 50%). Eventually, the carrier formed a 50:50 JV with TAV for the development, construction, and operation of the new passenger terminal. In this case, government owned Riga Airport took the initiative to ensure the building of the new terminal, whereas investing airBaltic, similar to the investing TAV group, seemed more conservative regarding the terminal investment. The difference in attitude between the government owned airport and the airline is in line with our model prediction.

The parameter scopes with different impacts on the ET investment timing decisions of the government and Airline 1 are presented in Figure 2.

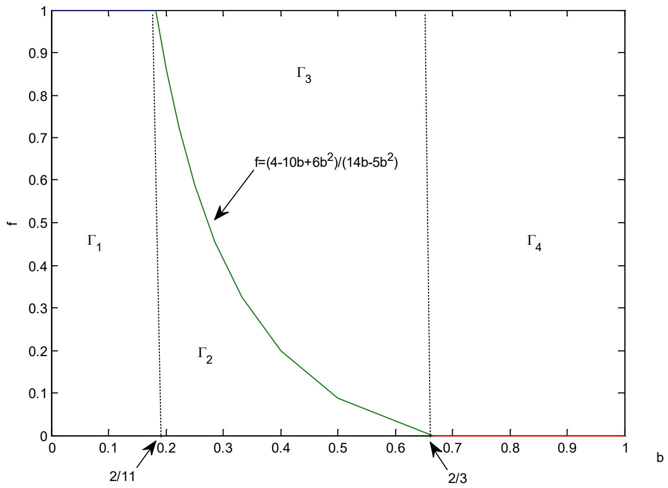

Figure 2 The parameter areas with respect to b and f

3.3.5 Subsidy to align the airline's investment timing to the social optimum

Based on Proposition 3, when $I \le \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$, the ET investment timing preferred by Airline 1 always coincides with that of the government. Therefore, in this section, we focus on the case when $I > \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$. Subsidies, common in the transportation industry, are critical for terminal investors to cover their budget deficits and thereby change their investment behavior. Now, we investigate a government using two types of subsidies: a lump-sum subsidy or a per-unit subsidy. A lump-sum subsidy is a fixed transfer given to Airline 1 after its ET investment, and a per-unit subsidy is based on the outputs from its ET and paid each period. Now, we discuss the government's regulation in a general setting, in which the ambiguity levels between the government and the Airline 1 may differ. Using the lump-sum subsidy, the government's regulation can be described as the following optimization problem.

$$\max_{v_{RL}, P} (\frac{v_0}{v_{RL}})^{\beta_G} [U(v_{RL}) - I] - \lambda P \tag{22a}$$

$$\text{s.t.} \quad (\frac{v_0}{v_{RL}})^{\beta_S} [\Pi_1(v_{RL}) - I] + P \ge 0 \tag{22b}$$

$$P \ge 0 \tag{22c}$$

where v_{RL} and P are the regulated ET investment timing and the lump-sum subsidy to Airline 1, respectively. $\lambda > 0$ indicates the shadow costs of a subsidy. The shadow cost of subsidy is the cost to collect the subsidy (public funds) by the government. Public funds are collected through taxes and fees, which add costs to the whole society (see Laffont and Tirole, 1993 for further discussions on this issue). In our model, the airline's profit is included in the government's objective function, and thereby the subsidy does not appear in the social welfare function, if the shadow cost of subsidy is omitted. The subsidy becomes the internal transfer payment between the government and airline 1 and does not affect social welfare. Thus, the social optimum can always be reached where the government can use unlimited subsidy to induce airline 1 to implement the regulated investment timing. This would be a trivial case to analyze. The Objective Function (22a) means that the government determines the regulated investment timing and the subsidy to maximize its option value, which equals the social welfare increment minus the shadow costs of the subsidy. Here, we use another form to represent the option functions of the government and airline 1, which is commonly used in the real options literature (see Azevedo and Paxson, 2014). Constraint (22b) is the participation constraint (PC), that is, Airline 1's option value under a regulation should not be less than its reserved value 0. Constraint (22c) requires a non-negative subsidy. We solve (22a)–(22c) and obtain Proposition 4.

Proposition 4. *Let* v_1 *and* v_2 *be the (minimum) positive root of the following equations*

$$[(\beta_G-2)\Phi_{2G}\omega_{2G}+(\beta_S-2)v^{\beta_G-\beta_S}\lambda\Phi_{2S}\omega_{2S}]v^2+[(\beta_G-1)\Phi_{1G}\omega_{1G}+(\beta_S-1)v^{\beta_G-\beta_S}\lambda\Phi_{1S}\omega_{1S}]v+\frac{\beta_G\omega_{0G}+\beta_S\lambda v^{\beta_G-\beta_S}\omega_{0S}}{r}=(\beta_G+\beta_S\lambda v^{\beta_G-\beta_S})I \tag{23}$$

$$\Phi_{2S}\omega_{2S}v^2+\Phi_{1S}\omega_{1S}v+\frac{\omega_{0S}}{r}=I\,, \tag{24}$$

respectively. A government's regulation rule under the lump-sum subsidy policy, v_{RL}^* and P^*, *can be expressed as follows:*

(i) if $v_G \ge v_2$, *then* $v_{RL}^* = v_G$, $P^* = 0$;

(ii) if $v_G < v_2$ *and* $v_1 \ge v_2$, *then* $v_{RL}^* = v_1$, $P^* = 0$;

(iii) if $v_G < v_2$ *and* $v_1 < v_2$, *then* $v_{RL}^* = v_1$, $P^* = (\frac{v_0}{v_{RL}^*})^{\beta_S}(I-\Phi_{2S}\omega_{2S}v_{RL}^{*2}-\Phi_{1S}\omega_{1S}v_{RL}^*-\frac{\omega_{0S}}{r})$.

Proposition 4 indicates that the regulation rule has a stepwise structure depending on the comparison results of three thresholds: the social optimum (v_G), an airline's break-even timing (v_2), and the mixed timing between the social optimum and the airline optimum (v_1). To understand Proposition 4, it is useful to analyze the government's basic tradeoff. A higher subsidy P can provide sufficient incentives to Airline 1 to invest in the ET earlier because it covers part of the cost (or equivalently reduce investment costs). However, the subsidy is costly to the government and simultaneously reduces social welfare (because the shadow costs of subsidy are positive). The government faces a tradeoff between the social welfare increment (arising from earlier ET construction) and a higher subsidy. Notably v_2 is the break-even timing for Airline 1 to construct the ET, $\Pi_1(v_2)=0$. We know that the necessary incentive to promote Airline 1 to make an ET investment is determined by the difference between the government's ideal timing v_G and Airline 1's break-even timing v_2. When $v_G \geq v_2$, Airline 1's PC Constraint (9b) can be satisfied when it implements the regulated investment timing. In other words, the government's ideal timing v_G can be implemented without any subsidy. When $v_G < v_2$, the government's ideal timing v_G cannot be implemented voluntarily, and the government has two options: subsidize Airline 1 to encourage early ET investment or wait until Airline 1's PC Constraint (9b) is satisfied. When $v_1 \geq v_2$, waiting is better and Airline 1's PC constraint can be satisfied without a subsidy. When $v_1 < v_2$, provision of a subsidy is necessary for Airline 1 to induce the outcome preferred by the government.

Using the per-unit subsidy, the government's regulation problem can be described as follows:

$$\max_{v_{RU},P} \left(\frac{v_0}{v_{RU}}\right)^{\beta_G} [U(v_{RU}) - I - \lambda \chi q_{11}] \tag{25a}$$

$$\text{s.t. } \left(\frac{v_0}{v_{RU}}\right)^{\beta_S} [\Pi_1(v_{RU}) - I + \chi q_{11}] \geq 0 \tag{25b}$$

$$\chi \geq 0 \tag{25c}$$

where v_{RU} and χ are the regulated ET investment timing and the unit subsidy to Airline 1, respectively. Equations (25a)–(25c) have similar meanings as (22a)–(22c). We solve (25a)–(25c) and obtain Proposition 5.

Proposition 5. *Let* v_3 *be the positive root of Equation (26)*

$$(\beta_G - 2)(\Phi_{2G}\omega_{2G} + \lambda\Phi_{2S}\omega_{2S})v^2 + (\beta_G - 1)(\Phi_{1G}\omega_{1G} + \lambda\Phi_{1S}\omega_{1S})v + \frac{\beta_G(\omega_{0G} + \lambda\omega_{0S})}{r} = (1+\lambda)\beta_G I \tag{26}$$

The government's regulation under the per-unit subsidy policy, v_{RU}^* and χ^*, *can be expressed as follows:*

(i) if $v_G \geq v_2$, *then* $v_{RU}^* = v_G$, $\chi^* = 0$;

(ii) if $v_G < v_2$ *and* $v_3 \geq v_2$, *then* $v_{RU}^* = v_3$, $\chi^* = 0$;

(iii) if $v_G < v_2$ *and* $v_3 < v_2$, *then* $v_{RU}^* = v_3$, $\chi^* = \dfrac{I - \Phi_{2S}\omega_{2S}v_{RU}^{*2} - \Phi_{1S}\omega_{1S}v_{RU}^* - \omega_{0S}/r}{\omega_{1q}v_{RU}^* + \omega_{0q}}$, *where*

$\omega_{1q} = \dfrac{4-b^2}{4(1-b)(2+2b-b^2)}$ *and* $\omega_{0q} = \dfrac{3bf - 2b + 2}{4(1-b)(2+2b-b^2)}$.

Comparing Proposition 4 and Proposition 5, it is clear that the two policies have similar stepwise structures. This finding leads to the following question: Are Proposition 4 and Proposition 5 equivalent, or do they have the same regulation outcomes? Corollary 3 answers this question.

Corollary 3. *If the government has the same ambiguity level as Airline 1,* $\kappa_S = \kappa_G = \kappa$*, the lump-sum subsidy policy and the per-unit subsidy policy have the same outcomes,* $v_{RL}^* = v_{RU}^*$*. Moreover, the two policies require the same budget in present value for the government.*

Corollary 3 reveals that the two subsidy policies can have equivalent effects: They lead to the same regulated ET timing and require the same amount of funds from the government if the government and Airline 1 have the same ambiguity levels. The lump-sum subsidy is based on the whole ET (or the supply side of the transportation service), and the per-unit subsidy is based on the numbers of passengers through the ET in each period (or the demand side of the transportation service). Because the market is in equilibrium and the government and the airline have the same attitude toward future uncertainty or risk, subsidizing the supply is equal to subsidizing the demand.

To better present the interaction between the government and Airline 1, we use the following options-game matrix (Chevalier-Roignant and Trigeorgis, 2011) to illustrate it. From Table 1, we observe that {Regulate, Invest ET} is the Nash equilibrium, which is consistent with our previous analysis.

Table 1 The options-game matrix between airline 1 and the government

		Airline 1: Invest ET	Airline 1: Not invest ET
Government	Subsidy	$\{(\frac{v_0}{v_{RL}^*})^{\beta_G}[U(v_{RL}^*)-I]-\lambda P^*,$ $(\frac{v_0}{v_{RL}^*})^{\beta_S}[\Pi_1(v_{RL}^*)-I]+P^*\}$	{0, 0}
	No subsidy	$\{(\frac{v_0}{v_S})^{\beta_G}[U(v_S)-I],(\frac{v_0}{v_S})^{\beta_S}[\Pi_1(v_S)-I]\}$	{0, 0}

Note: The left expressions or numbers in each cell are the government's payoff, whereas the right ones are airline 1's payoff.

3.3.6 A numerical example

To better illustrate the conclusions obtained, a numerical example is presented in this section. The parameters are as follows: $r = 0.1$, $\mu = 0.03$, $\sigma = 0.01, b = 0.5$, $I = 50$, $f = 0.08$, $\lambda = 0.3$, and $\kappa_S = \kappa_G = \kappa \in [0,5]$.[3] The effects of ambiguity on the ET investment timing of Airline 1 and the

[3] According to Schröder (2011), κ should be restricted to $\kappa < (r-\mu)/\sigma$. In his numerical examples, $r = 0.1$,

government are shown in Figure 2. In this example, $\frac{2}{11} < b = 0.5 < \frac{2}{3}$, $f = 0.08 < \frac{4-10b+6b^2}{14b-5b^2} = 0.086$, that is, $(b, f) \in \Gamma_2$; thus, we find that the social optimum v_G is always earlier than Airline 1's preferred v_S, and their difference widens as κ increases. In addition, Figure 3 and Figure 4 illustrate the regulated ET investment timing and the related subsidy. When $\kappa \le 1.4$, $v_G \ge v_2$, the regulated timing is v_G and the subsidy is 0. When $1.4 < \kappa \le 1.6$, $v_G < v_2$, and $v_1 \ge v_2$, the regulated timing is v_1 and the subsidy is still 0. When $\kappa > 1.6$, $v_G < v_2$, and $v_1 < v_2$, the regulated timing is v_1 and the subsidy is positive and increases in κ because the difference between the regulated timing v_1 and Airline 1's break-even timing v_2 widens and thus more subsidy is necessary to cover the investment deficit.

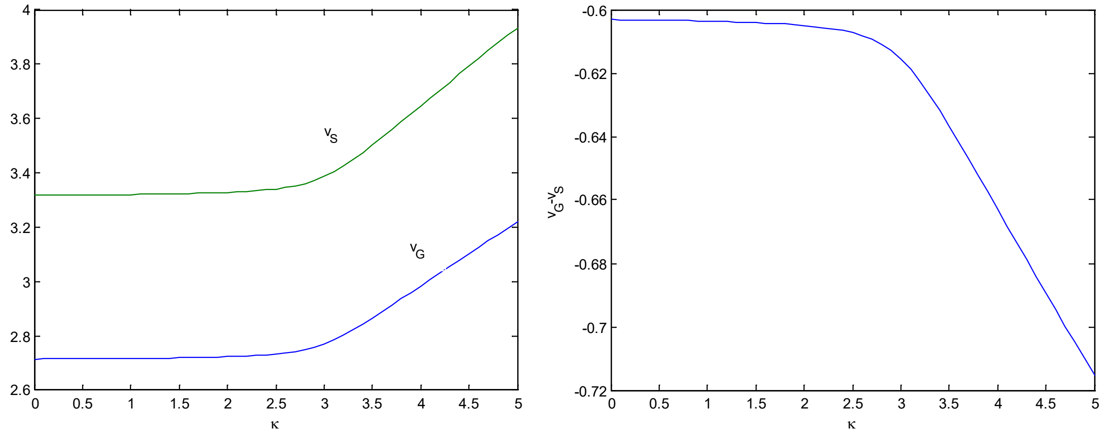

Figure 3. The effects of ambiguity level on the ET investment timing of airline 1 and the government

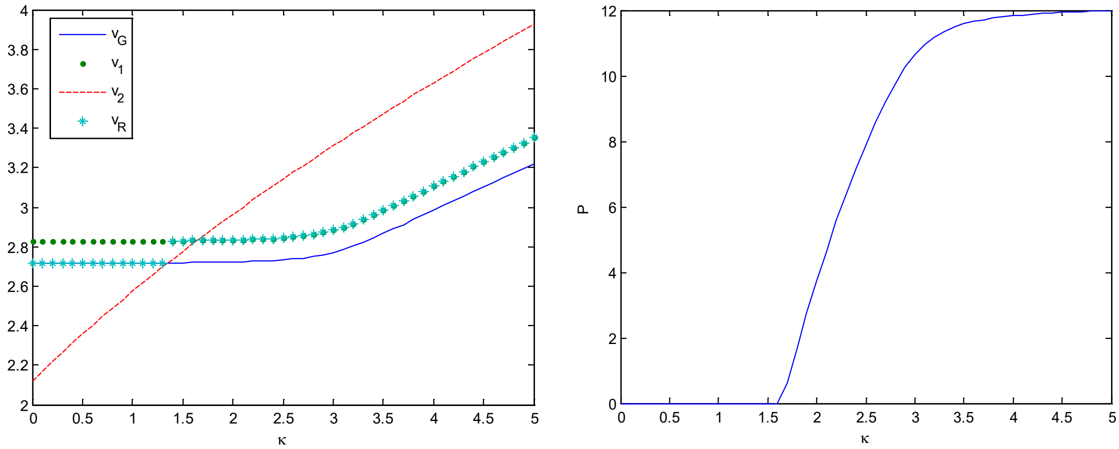

Figure 4. The government's subsidy policy

$\mu = 0.05$ and $\sigma = 0.2$, therefore $\kappa \le 0.2$. In our numerical example here, $r = 0.1$, $\mu = 0.03$ and $\sigma = 0.01$, therefore κ should be restricted to $\kappa \le 7$. In other words, the relative higher value of κ in our example is due to the lower value of σ, compared to the Schröder (2011)'s cases.

4. Extensions

Although infrastructure investors are usually considered ambiguity-averse, on some occasions, they can also be considered as ambiguity-loving. In reality, one type of ambiguity loving behavior is being overly optimistic and in favor of high-yield but low-probability gains. For instance, research has shown that air travel demand forecasts tended to be positively biased, suggesting over-optimism and over-confidence in airport capacity investment (OECD 2016). Wojahn (2012) asserts that the airline industry has always been plagued by over-investment and analyzes the underlying reasons. He suggests that airline managers tend to send overly optimistic signals to shareholders due to the principal–agent problem. He also asserts that the state may be overly bullish toward airline investment because it follows an agenda motivated by considerations other than the economic success of the airline, such as the prestige of a having a large flag carrier, securing or creating jobs, and the positive externalities of aviation. It is worth pointing out that this type of "over-optimism" is in fact quite common during a country's construction bubble. For example, it has been argued that a number of airports in Spain are "white elephant" projects that yielded little return. The Ciudad Real Central Airport waited 9 years for its first commercial flight. In Japan, the Osaka Kansai airport and Kobe airport, both built on expensive man-made island, have been under-utilized for extended periods. Despite the high cost and original plan of serving as a hub airport, the Montreal Mirabel Airport's passenger terminal had to be demolished and the airport has since been utilized for cargo and general aviation only. Under the RMB 4 trillion (USD 586 billion) stimulus package from the central government of China in 2008, many local governments also showed unprecedented enthusiasm to construct public infrastructures including airports, which causes severe capacity excessiveness and fierce competition (Xu and Chin, 2012). While such aggressive investments on low-yield projects may be caused by many factors jointly, ambiguity loving behaviour is likely one of the drivers behind. To cover such scenarios in our study, we first consider a case in which both Airline 1 and the government are ambiguity-loving. Next, we explore more possibilities, for example, an ambiguity-averse Airline 1 and an ambiguity-loving government or the opposite scenario.

4.1 Both Airline 1 and the government are ambiguity-loving

Now, we define ambiguity-loving Airline 1's present value of the future profit increment as follows:

$$\Pi_{1L} = \sup_{\theta \in \mathrm{K}} E^{Q^{\theta}}[\int_0^{\infty} e^{-rt} \Delta\pi_{1t} dt \mid F_t] \tag{27}$$

where subscript "L" denotes the case of complete ambiguity-loving. Based on the same reasoning used in Section 3.2, we assume that $\mu - \sigma\theta_t < r$, which leads to $\kappa < (r-\mu)/\sigma$, under the completely ambiguity-loving case. This assumption is quite standard in the literature on ambiguity (e.g., Schröder 2011). Similarly, we define the completely ambiguity-loving government's present value of the future social welfare increment as follows:

$$U_L = \sup_{\theta \in \mathrm{K}} E^{Q^{\theta}}[\int_0^{\infty} e^{-rt} \Delta u_t dt \mid F_t] \tag{28}$$

With analyses similar to those in Sections 3.3.2 to 3.3.5 (details in Appendix C), we find that most conclusions in the case of an ambiguity-loving decision maker are similar to those in the ambiguity-averse case, except that ambiguity has positive effects on Airline 1's expected present value of the future profit increment and the government's expected present value of future social welfare increment. When Airline 1 (or the government) is ambiguity-loving, it only cares about the best case ($\theta_t = \kappa$); in other words, it only looks forward to the upside potential and neglects the downside risk. This phenomenon leads to the upward influence of ambiguity on the prospect. Moreover, if the government has the same ambiguity level as Airline 1, $\kappa_S = \kappa_G = \kappa$, conclusions similar as those in Proposition 3 can be obtained for the government and Airline 1's investment timing choices, except that the term "κ" is replaced by "$-\kappa$". Moreover, the ambiguity-loving government can use similar regulations to align ambiguity-loving Airline 1's investment timing with a socially optimal choice through the subsidy. The findings are similar to those identified in Proposition 4 and 5, except that terms "κ_S" and "κ_G" are replaced by "$-\kappa_S$" and "$-\kappa_G$", respectively.

4.2 Alternative scenarios

When ambiguity-loving Airline 1 must interact with an ambiguity-averse government, its preferred investment timing is earlier, and the social optimum remains the same compared with the case in Section 3. Therefore, their preferred timing difference narrows when $(b, f) \in \Gamma_1 \cup \Gamma_2$. When ambiguity-averse Airline 1 faces an ambiguity-loving government, the airline's preferred investment timing remains the same, and the social optimum is earlier than the case in Section 3. Therefore, the difference between preferred timings widens when $(b, f) \in \Gamma_1 \cup \Gamma_2$. The comparisons of preferred ET investment timing under four scenarios are summarized in the following table.

The analytical results reported in Table 2 suggest the following management insights: (1) When the ET investment is sufficiently small, the preferred ET investment timing of Airline 1 and the government can coincide without regulations regardless of their ambiguity attitude (ambiguity-averse or ambiguity-loving) because both are willing to invest immediately. (2) When the ET investment is not very low, the competition between the airlines is not very intensive, or the PT charge is not very high ($(b, f) \in \Gamma_1 \cup \Gamma_2$), the government always prefers earlier investment than Airline 1 if their ambiguity attitude is the same. If their ambiguity attitude differs, the combination of an ambiguity-averse government and ambiguity-loving Airline 1 alleviates their interest conflict, and the combination of an ambiguity-loving government and ambiguity-averse Airline 1 exaggerates their interest conflict. (3) When the ET investment is not very low, the competition between the airlines is intensive, or the PT charge is high ($(b, f) \in \Gamma_3 \cup \Gamma_4$), the comparisons of ET investment timing are always uncertain under any combination.

Table 2 The comparisons of the preferred ET investment timing between airline 1 and the government when their ambiguity levels are the same

	Ambiguity-averse airline 1	Ambiguity-loving airline 1

Ambiguity-averse government	If $I \le \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$, then $v_S = v_G = v_0$	If $I \le \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$, then $v_S = v_G = v_0$
	If $I > \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$ and $(b, f) \in \Gamma_1 \cup \Gamma_2$, then $v_S > v_G$	If $I > \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$ and $(b, f) \in \Gamma_1 \cup \Gamma_2$, then their difference is narrowed.
	If $I > \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$ and $(b, f) \in \Gamma_3 \cup \Gamma_4$, then their comparison is uncertain.	If $I > \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$ and $(b, f) \in \Gamma_3 \cup \Gamma_4$, then their comparison is uncertain.
Ambiguity-loving government	If $I \le \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$, then $v_S = v_G = v_0$	If $I \le \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$, then $v_S = v_G = v_0$
	If $I > \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$ and $(b, f) \in \Gamma_1 \cup \Gamma_2$, then their difference is widened.	If $I > \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$ and $(b, f) \in \Gamma_1 \cup \Gamma_2$, then $v_S > v_G$
	If $I > \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$ and $(b, f) \in \Gamma_3 \cup \Gamma_4$, then their comparison is uncertain.	If $I > \min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$ and $(b, f) \in \Gamma_3 \cup \Gamma_4$, then their comparison is uncertain.

5. Discussion and Conclusions

In this paper, we model an airline's investment timing decision when it vertically invests in exclusive airport facilities. The effects of airline competition and demand ambiguity are explicitly considered. We find that for the investing airline, the optimal investment timing rule requires the expected present value of its future profit increment to exceed the investment cost by the option value multiplier. In other words, covering investment cost alone is insufficient to justify an airline's ET investment because demand ambiguity must be compensated with higher returns. Additionally, if the airline is pessimistic (or optimistic), demand ambiguity always delays (or promotes) vertical investment. In the absence of fierce airline competition, an airline's vertical investment is later than the social optimum, and increasing ambiguity deviates an airline's ET investment timing further from the socially optimal level. In addition, an increase in PT charge accelerates an airline's ET investment. Furthermore, we show that a government can use a lump-sum subsidy or a per-unit subsidy to regulate an airline's ET investment behavior. Both subsidy policies have stepwise structures, and the regulated ET investment timing depends on the comparisons of three thresholds: the social optimum, the airline's break-even timing, and the mixed timing between the social optimum and the airline optimum. In addition, the larger shadow costs of a subsidy delay the regulated ET timing.

These theoretical results have policy implications. First, although an airline may benefit significantly from its vertical investment in exclusive airport facilities, demand uncertainty (e.g., ambiguity) delays such investments. The resultant investment timing is later than the social optimum, especially where there is insufficient airline competition. Our analytical results suggest that airline competition leads to lower airfares and contributes to larger and earlier airline vertical investments in airports in the presence of demand ambiguity. Whereas airlines' vertical investments in airports may result in many benefits, regulatory attention may be necessary in markets with insufficient airline competition.

Second, demand ambiguity is expected to reduce and delay airlines' vertical investments in airport facilities. In the aviation industry, some airports provide airlines with detailed market and operation information as a means to attract and maintain airline services (Lohmann and Vianna 2016; Fu and Yang 2017). Our analytical results suggest that such practices also help airports secure long-term investments. The benefits of better information (and less ambiguity) have not been well recognized in the literature. Further analysis and more regulatory attention may be justified.

Finally, our study suggests a means for the government to influence an airline's ET investment behavior: PT charge, and thus the associated market access regulation and subsidies. The PT charge influences the outputs and the investing timing of the competing ET and can thus be used to influence a private investor's decision indirectly. Our analytical results also suggest that airline competition promotes vertical airport investment. Such an effect has not been considered in related policy evaluations. For example, Gillen et al. (2016) assert that although schedule-coordinated airports experience moderate delays, slot control may lead to underuse of airport capacity (Morisset and Odoni 2011) and barriers to competition (Czerny et al. 2008). The unrestricted approach to airport access at most US airports provides airlines flexibility in operation and leads to better airport capacity utilization but more significant delays. Our results provide additional support for the unrestricted airport access approach because increased airline competition promotes vertical investments in airports; thus, excessive delays may be alleviated in the long term.

To ensure mathematical tractability, we used simplifying assumptions in our analysis, with certain important factors not fully considered in the model. For example, airlines' network structure has important implications on airline competition and airport investments. The forms of airport regulation and capacity/slot allocation also significantly influence the decisions of airlines and airports. Therefore, further research could extend our model to a network setting under alternative airport regulatory regimes to discover fresh insights. Last but not the least, although we believe much of our analysis can be generalized to other transport sectors (e.g. the maritime industry), a more in-depth investigation is necessary to ensure that our model reflects essential market reality in these industries. We hope our study could lead to more advanced studies on this important topic, so that both theoretical improvements and practical managerial insights can be obtained.

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Appendix A Airline 1's profit and social welfare in the single period without ET

When there is no ET, the demand system becomes:

$$p_{12} = 1 - q_{12} - bq_2 \tag{29}$$

$$p_2 = 1 - q_2 - bq_{12} \tag{30}$$

The profit functions of the two airlines are:

$$\pi_1 = (p_{12} - f)q_{12} \tag{31}$$

$$\pi_2 = (p_2 - f)q_2 \tag{32}$$

Substituting (29) and (30) into (31) and (32), the equilibrium outputs of the two airlines in the case without ET are:

$$q_2 = q_{12} = \frac{1-f}{2+b} \tag{33}$$

Then we can obtain airline 1's single period profit as

$$\pi_1 = \frac{(1-f)^2}{(2+b)^2} \tag{34}$$

Meanwhile, the social welfare function in the case without ET becomes:

$$u(q_{12}, q_2) = q_{12} + q_2 - (q_{12}^2 + q_2^2 + 2bq_{12}q_2)/2 \tag{35}$$

Substituting (33) into (35), we can obtain the single period social welfare in the case without ET as:

$$u = \frac{(1-f)[(1+f)b + 3 + f]}{(2+b)^2} \tag{36}$$

Appendix B Proofs of the propositions and corollaries

Proof of Proposition 1a:

$$\text{Let } \Delta\pi_{1t} = \Delta\pi_{2S,t} + \Delta\pi_{1S,t} + \omega_{0S} \tag{37}$$

where $\Delta\pi_{2S,t} = w_{2S}v_t^2$ and $\Delta\pi_{1S,t} = w_{1S}v_t$. We apply the Ito lemma to $\Delta\pi_{2S,t}$ and obtain

$$d\Delta\pi_{2S,t} = \omega_{2S}v_t^2[(2\mu - 2\sigma\theta_t + \sigma^2)dt + 2\sigma dB_t^\theta].$$

Therefore, $$\Delta\pi_{2S,t} = \Delta\pi_{2S,0}\exp[(2\mu - \sigma^2)t - 2\sigma\int_0^t \theta_s ds + 2\sigma B_t^\theta)] \tag{38}$$

We also apply the Ito lemma to $\Delta\pi_{1S,t}$ and obtain

$$d\Delta\pi_{1S,t} = w_{1S}v_t[(\mu - \sigma\theta_t)dt + \sigma dB_t^\theta].$$

Therefore, $$\Delta\pi_{1S,t} = \Delta\pi_{1S,0}\exp((\mu - \frac{1}{2}\sigma^2)t - \sigma\int_0^t \theta_s ds + \sigma B_t^\theta). \tag{39}$$

We plug (37), (38), and (39) into (13) and obtain

$$\begin{aligned}
&\inf_{\theta\in K_S} E^{Q^\theta}[\int_0^\infty e^{-rt}\Delta\pi_{1t}dt \mid F_t] = \inf_{\theta\in K_S}\int_0^\infty E_0^\theta[e^{-rt}(\Delta\pi_{2S,0}\exp(2\mu t - \sigma^2 t - 2\sigma\int_0^t \theta_s ds + 2\sigma B_t^\theta) \\
&+\Delta\pi_{1S,0}\exp((\mu - \frac{1}{2}\sigma^2)t - \sigma\int_0^t \theta_s ds + \sigma B_t^\theta) + \omega_{0S})]dt \\
&= \int_0^\infty [\Delta\pi_{2S,0}\exp((2\mu - r - \sigma^2)t)\cdot \inf_{\theta\in K_S} E_0^\theta(\exp(2\sigma(B_t^\theta - \int_0^t \theta_s ds))) \\
&+\Delta\pi_{1S,0}\exp((\mu - r - \frac{1}{2}\sigma^2)t)\cdot \inf_{\theta\in K_S} E_0^\theta(\exp(\sigma(B_t^\theta - \int_0^t \theta_s ds))) + \omega_{0S}\exp(-rt)]dt
\end{aligned} \tag{40}$$

Notably, $\theta_t \in K_S = [-\kappa_S, \kappa_S]$; thus, we know that

$$\begin{aligned}
&E_0^\theta[\exp(2\sigma(B_t^\theta - \int_0^t \theta_s ds))] \ge E_0^\theta[\exp(2\sigma(B_t^\theta - \int_0^t \kappa_S ds))] = E_0^\theta[\exp(2\sigma(B_t^\theta - \kappa_S t))] \\
&= \exp(2\sigma^2 t - 2\sigma\kappa_S t)
\end{aligned}$$

$$\begin{aligned}
&E_0^\theta[\exp(\sigma(B_t^\theta - \int_0^t \theta_s ds))] \ge E_0^\theta[\exp(\sigma(B_t^\theta - \int_0^t \kappa_S ds))] = E_0^\theta[\exp(\sigma(B_t^\theta - \kappa_S t))] \\
&= \exp(\frac{1}{2}\sigma^2 t - \sigma\kappa_S t)
\end{aligned}$$

Therefore, $\inf_{\theta\in K_S} E^\theta[\exp(2\sigma(B_t^\theta - \int_0^t \theta_s ds))] = \exp(2\sigma^2 t - 2\sigma\kappa_S t)$ and

$$\inf_{\theta\in K_S} E^\theta[\exp((B_t^\theta - \int_0^t \theta_s ds)\sigma)] = \exp(\frac{1}{2}\sigma^2 t - \sigma\kappa_S t). \tag{41}$$

We plug (41) into (40) and obtain

$$\inf_{\theta\in K_S} E^{Q^\theta}[\int_0^\infty e^{-rt}\Delta\pi_{1t}dt \mid F_t] = \Delta\pi_{2S,0}\int_0^\infty [\exp((2\mu-r-\sigma^2)t)\cdot\exp(2\sigma^2 t - 2\sigma\kappa_S t)]dt +$$
$$\Delta\pi_{1S,0}\int_0^\infty [\exp((\mu-r-\frac{1}{2}\sigma^2)t)\cdot\exp(\frac{1}{2}\sigma^2 t-\sigma\kappa_S t)]dt + \frac{\omega_{0S}}{r}$$
$$= \Delta\pi_{2S,0}\int_0^\infty \exp((2\mu-2\kappa_S\sigma+\sigma^2-r)t)+\exp((\mu-\kappa_S\sigma-r)t)dt + \frac{\omega_{0S}}{r} \tag{42}$$
$$= \frac{w_{2S}v_0^2}{r-2(\mu-\kappa_S\sigma)-\sigma^2} + \frac{w_{1S}v_0}{r-(\mu-\kappa_S\sigma)} + \frac{\omega_{0S}}{r}$$

which is (14). □

Proof of Proposition 1b:

The proof is organized as follows: Step 1 proves that Airline 1's preference form (13) satisfies the dynamic consistency; Step 2 finds the Hamilton–Jacobi–Bellman equation of the Problem (15) and solves it; Step 3 uses the solution obtained in Step 2 and the corresponding boundary conditions to find the optimal ET investment rule preferred by Airline 1.

First, the dynamic consistency property of Airline 1's preference form in (13) can be obtained using a similar approach such as in Nishimura and Ozaki (2007) or Schröder (2011).

Second, when Airline 1 attempts to make an ET investment decision, it has two choices: invest now (at time 0) or hold the option and consider whether to invest in ET at time dt. We investigate the RHS of (15) and obtain

$$\max_{\tau\ge 0}\inf_{\theta\in K_S} E^{Q^\theta}(\int_\tau^\infty e^{-rt}\Delta\pi_{1t}dt - e^{-r\tau}I \mid F_t)$$
$$= \max[\inf_{\theta\in K_S} E^{Q^\theta}(\int_0^\infty e^{-rt}\Delta\pi_{1t}dt \mid F_t) - I, \max_{\tau\ge dt}\inf_{\theta\in K_S} E^{Q^\theta}(\int_\tau^\infty e^{-rt}\Delta\pi_{1t}dt - e^{-r\tau}I \mid F_t)]$$
$$= \max[\Pi_1 - I, \max_{\tau\ge dt}\inf_{\theta\in K_S} E^{Q^\theta}(\int_\tau^\infty e^{-rt}\Delta\pi_{1t}dt - e^{-r\tau}I \mid F_t)]$$
$$= \max[\Pi_1 - I, e^{-rdt}\max_{\tau\ge dt}\inf_{\theta\in K_S} E^{Q^\theta}(E^{Q^\theta}(\int_\tau^\infty e^{-r(t-dt)}\Delta\pi_{1t}dt - e^{-r(\tau-dt)}I \mid F_{t+dt}) \mid F_t)]$$
$$= \max[\Pi_1 - I, e^{-rdt}\max_{\tau\ge dt}\inf_{\theta\in K_S} E^{Q^\theta}(\inf_{\theta'\in K_S} E^{Q^{\theta'}}(\int_\tau^\infty e^{-r(t-dt)}\Delta\pi_{1t}dt - e^{-r(\tau-dt)}I \mid F_{t+dt}) \mid F_t)] \tag{43}$$
$$= \max[\Pi_1 - I, e^{-rdt}\inf_{\theta\in K_S} E^{Q^\theta}(\max_{\tau\ge dt}\inf_{\theta'\in K_S} E^{Q^{\theta'}}(\int_\tau^\infty e^{-r(t-dt)}\Delta\pi_{1t}dt - e^{-r(\tau-dt)}I \mid F_{t+dt}) \mid F_t)]$$
$$= \max[\Pi_1 - I, e^{-rdt}\inf_{\theta\in K_S} E^{Q^\theta}(V_{t+dt} \mid F_t)]$$
$$= \max[\Pi_1 - I, (1-rdt)(\inf_{\theta\in K_S} E^{Q^\theta}(dV_t \mid F_t) + V_t)]$$
$$= \max[\Pi_1 - I, \inf_{\theta\in K_S} E^{Q^\theta}(dV_t \mid F_t) + V_t - rV_t dt]$$

In (43), the first equality means that Airline 1 must compare its decisions between investing now (at time 0) versus waiting for a short time interval dt and reconsidering whether to invest. The second equality uses the definition of Π_1. The third equality uses the law of iterated integrals. The fourth equality uses the rectangularity[4]. The fifth equality uses τ is greater than or equal to dt. The sixth equality uses the definition of the first term of V. The seventh equality substitutes V_{t+dt} with $dV_t + V_t$ and e^{-rdt} with $1-rdt$. The final equality eliminates the term that is of a higher order than dt.

Next, we obtain the following Hamilton–Jacobi–Bellman equation:

$$V = \max[\Pi_1 - I, \inf_{\theta \in \mathrm{K}_S} E^{Q^\theta}(dV_t \mid F_t) + V_t - rV_t dt] \tag{44}$$

where the first term in the RHS is the value of investing now and the second term is the expected value of waiting. We have

$$\begin{aligned}
&\inf_{\theta \in \mathrm{K}_S} E^{Q^\theta}(dV_t \mid F_t) = \inf_{\theta \in \mathrm{K}_S} E^{Q^\theta}[V'(v_t)((\mu - \sigma\theta_t)v_t dt + \sigma v_t dB_t^\theta) + \frac{1}{2}\sigma^2 v_t^2 V''(v_t)dt \mid F_t] \\
&= \min_{\theta \in \mathrm{K}_S}[V'(v_t)((\mu - \sigma\theta_t)v_t dt + \frac{1}{2}\sigma^2 v_t^2 V''(v_t)dt] \\
&= [V'(v_t)((\mu - \sigma\kappa_S)v_t + \frac{1}{2}\sigma^2 v_t^2 V''(v_t)]dt
\end{aligned} \tag{45}$$

where V'' denotes $\partial^2 V / \partial v^2$, and V' denotes $\partial V / \partial v$. In (44), the first equality holds by using the Ito lemma; the second equality holds because (B_t^θ) is the Brownian motion with respect to Q^θ.

Plugging (45) into the RHS of Problem (15), we transform it to the following ordinary differentiation equation (ODE):

$$1/2\sigma^2 v^2 V'' + (\mu - \kappa\sigma)vV' - rV = 0 \tag{46}$$

We solve ODE (46) obtain its solution as follows:

$$V(v) = A_1 v^{\beta_1} + A_2 v^{\beta_2} \tag{47}$$

where A_1 and A_2 are the coefficients yet to determined. β_1 and β_2 are the two solutions of the quadratic Equation (48) with $\beta_1 > 1$ and $\beta_2 < 0$.

$$1/2\sigma^2 \beta(\beta - 1) + \gamma\beta - r = 0 \tag{48}$$

where $\gamma = \mu - \kappa_S \sigma$.

Next, we use Solution (47) and the following boundary conditions to find the optimal ET investment rule. We easily obtain the next boundary condition:

$$V(0) = 0 \tag{49}$$

From (47) and (49), we know that $A_2 = 0$. This leaves

$$V(v) = A_1 v^{\beta_1} \tag{50}$$

Notably, the risk-adjusted discount rates under ambiguity are both positive, leading to $r - 2(\mu - \kappa_S \sigma) - \sigma^2 > 0$. This inequality is equivalent to Inequality (51):

---

[4] According to Lemma B3 of Nishimura and Ozaki (2007), if the random variable is F_{T-} measurable and Θ is a strongly rectangular set of density generators, the recursive structure or the dynamic consistency can be satisfied as long as the minima exists. In our case, because the random variable v_t (and its quadratic term) are F_{T-} measurable, and Θ is strongly rectangular (according to its definition in Section 3.2), the dynamic consistency can still be satisfied.

$$1/2\sigma^2\phi(\phi-1)+(\mu-\kappa_S\sigma)\phi-r<0 \tag{51}$$

when $\phi=2$.

We compare (48) and (51) and obtain that $\beta_1>2$.

From the value-matching condition, we have

$$V(v^*)=\Pi_1^*-I \tag{52}$$

where v^* is Airline 1's ET investment threshold, and Π_1^* is its expected present value under v^*. In other words, Airline 1 must invest in the ET (or exercise its holding option) when the stochastic variable v reaches v^*. Moreover, from the smooth-pasting condition we have

$$\frac{\partial V(v^*)}{\partial v}=\frac{\partial \Pi_1^*}{\partial v} \tag{53}$$

We substitute (14) and (50) into (52) and (53) and obtain (16) after rearrangement.

If $I\le \omega_{0S}/r$, the quadratic Equation (16) has no positive root; thus, V is positive even when $v=0$. Therefore, an airline can immediately make the ET investment from the beginning, that is, $v_S=v_0$. If $I>\omega_{0S}/r$, quadratic Equation (16) has only one positive root, which is Airline 1's optimal ET investment timing that is later than the beginning time. □

Proof of Corollary 1b:

Let $B_{2S}=1-\dfrac{2}{\beta_S}$, $X_{2S}=\Phi_{2S}B_{2S}$ and $B_{1S}=1-\dfrac{1}{\beta_S}$, $X_{1S}=\Phi_{1S}B_{1S}$. We have $\dfrac{\partial X_{2S}}{\partial\kappa}=\dfrac{\partial X_{2S}}{\partial\Phi_{2S}}\cdot\dfrac{\partial\Phi_{2S}}{\partial\kappa}+\dfrac{\partial X_{2S}}{\partial B_{2S}}\cdot\dfrac{\partial B_{2S}}{\partial\kappa}$ and $\dfrac{\partial X_{1S}}{\partial\kappa}=\dfrac{\partial X_{1S}}{\partial\Phi_{1S}}\cdot\dfrac{\partial\Phi_{1S}}{\partial\kappa}+\dfrac{\partial X_{1S}}{\partial B_{1S}}\cdot\dfrac{\partial B_{1S}}{\partial\kappa}$ We know that $\dfrac{\partial X_{2S}}{\partial\Phi_{2S}}=1-\dfrac{2}{\beta_S}$, $\dfrac{\partial\Phi_{2S}}{\partial\kappa}=\dfrac{-2\sigma}{(r-2\mu+2\kappa\sigma-\sigma^2)^2}$, $\dfrac{\partial X_{2S}}{\partial B_{2S}}=\Phi_{2S}$, and $\dfrac{\partial B_{2S}}{\partial\kappa}=\dfrac{2}{\beta_S\chi_S\sigma}$, where $\chi_S=\sqrt{(\dfrac{\gamma_S}{\sigma^2}-\dfrac{1}{2})^2+\dfrac{2r}{\sigma^2}}$. Therefore, $\dfrac{\partial X_{2S}}{\partial\kappa}=\dfrac{2}{\beta_S\sigma}[\dfrac{\Phi_{2S}}{\chi_S}-\dfrac{(\beta_S-2)\sigma^2}{(r-2\mu+2\kappa\sigma-\sigma^2)^2}]$. We perform a calculation and obtain that $\Phi_{2S}(r-2\mu+2\kappa\sigma-\sigma^2)^2<(\beta_S-2)\chi_S\sigma^2$, which leads to $\partial X_S/\partial\kappa<0$. Moreover, $\dfrac{\partial X_{1S}}{\partial\Phi_{1S}}=1-\dfrac{1}{\beta_S}$, $\dfrac{\partial\Phi_{1S}}{\partial\kappa}=\dfrac{-\sigma}{(r-\mu+\kappa\sigma)^2}$, $\dfrac{\partial X_{1S}}{\partial B_{1S}}=\Phi_{1S}$, and $\dfrac{\partial B_{1S}}{\partial\kappa}=\dfrac{1}{\beta_S\chi_S\sigma}$. Therefore, $\dfrac{\partial X_{1S}}{\partial\kappa}=\dfrac{1}{\beta_S\sigma}[\dfrac{\Phi_{1S}}{\chi_S}-\dfrac{(\beta_S-1)\sigma^2}{(r-\mu+\kappa\sigma)^2}]$. We perform a calculation and obtain that $\Phi_{1S}(r-\mu+\kappa\sigma)^2<(\beta_S-1)\chi_S\sigma^2$, which leads to $\partial X_{1S}/\partial\kappa<0$. Because $\omega_{2S}>0$, $\partial\omega_{2S}/\partial\kappa=0$, $\omega_{1S}>0$, $\partial\omega_{1S}/\partial\kappa=0$, and $\partial\omega_{0S}/\partial\kappa=0$, from (16), we obtain $\partial v_S/\partial\kappa>0$. □

Proof of Corollary 1c:

In Airline 1's optimal ET investment rule (16), ω_{1S} and ω_{0S} are related to f. Therefore, to find the sign of $\partial v_S / \partial f$, we must calculate $\partial \omega_{1S} / \partial f$ *and* $\partial \omega_{0S} / \partial f$. We know that $\dfrac{\partial \omega_{1S}}{\partial f} = \dfrac{b^4 - 8b^3 + 4b^2 + 12b}{4(1-b)(2+2b-b^2)^2} > 0$ and

$$\frac{\partial \omega_{0S}}{\partial f} = \frac{(4-3f)b^6 - 4b^5 - (36f-12)b^4 + (48f-52)b^3 + (57f-8)b^2 + 48b}{4(1-b)(4+6b-b^3)^2}.$$

Because $\dfrac{\partial^2 \omega_{0S}}{\partial f^2} = \dfrac{-3b^6 - 36b^4 + 48b^3 + 57b^2}{4(1-b)(4+6b-b^3)^2} > 0$, $\dfrac{\partial \omega_{0S}}{\partial f}$ is an increase function with respect to f. When $f = 0$, $\dfrac{\partial \omega_{0S}}{\partial f} \geq 0$. Therefore, $\dfrac{\partial \omega_{0S}}{\partial f}$ is always positive for $b \in [0,1)$ and $f \in [0,1)$. Because $\Phi_{1S}(1 - \dfrac{2}{\beta_S}) > 0$, we have $\partial v_S / \partial f \leq 0$. □

Proof of Proposition 2a:

Use the similar logic as the proof in Proposition 1a. □

Proof of Proposition 2b:

Use the similar logic as the proof in Proposition 1b. □

Proof of Corollary 2a:

Use the similar logic as the proof in Corollary 1b. □

Proof of Proposition 3:

If $I \leq \min(\dfrac{\omega_{0S}}{r}, \dfrac{\omega_{0G}}{r})$, we can directly obtain that $v_S = v_G = v_0$ from Propsosition 1b and Proposition 2b.

If $I > \min(\dfrac{\omega_{0S}}{r}, \dfrac{\omega_{0G}}{r})$, to compare v_S and v_G, we must analyze the coefficients in (16) and (19). We perform a calculation and obtain that $\omega_{2G} - \omega_{2S} = \dfrac{4-b^2}{16(1-b)(2+2b-b^2)} > 0$,

$$\omega_{1G}-\omega_{1S}=\frac{(4+f)b^2-4(2+f)b+4}{8(1-b)(2+2b-b^2)} \quad \text{and} \quad \omega_{0G}-\omega_{0S}=\frac{(2-2b+3bf)[(6+5f)b^2-2(5+7f)b+4]}{16(1-b)(4+6b-b^3)} .$$

Therefore, when $b\in[0,\frac{2}{11}]$, or $b\in[\frac{2}{11},\frac{2}{3}]\cap f\in[0,\frac{4-10b+6b^2}{14b-5b^2}]$, we have $\omega_{1G}\geq\omega_{1S}$ and $\omega_{0G}\geq\omega_{0S}$. Because $\Phi_{2S}=\Phi_{2G}=\Phi_2>0$, $\Phi_{1S}=\Phi_{1G}=\Phi_1>0$, $\gamma_S=\gamma_G=\gamma$, and $\beta_S=\beta_G=\beta$, we compare (16) and (19) and obtain that $v_G<v_S$ always holds in the aforementioned parameter areas with respect to b and f. In the other parameter areas, the comparison of v_S and v_G is uncertain. □

Proof of Proposition 4:

If $v_G\geq v_2$, we easily verify that v_G satisfies Constraint (22b) when $P=0$. Problem (22a)–(22c) becomes an unconstraint optimization problem as follows:

$$\max_{v_R}(\frac{v_0}{v_R})^{\beta_G}[U(v_R)-I] \tag{54}$$

Solving (54) leads to $v_R^*=v_G$, which proves Part (i) of Proposition 4.

If $v_G<v_2$, Constraint (22b) cannot be satisfied with $P=0$ and $v_R^*=v_G$. In Objective Function (22a), we observed that the coefficient of the positive decision variable P is negative. Therefore, to maximize (22a), Constraint (22b) is binding, and the following equation must hold at the optimum.

$$P=(\frac{v_0}{v_R})^{\beta_S}(I-\Phi_{2S}\omega_{2S}v_R^2-\Phi_{1S}\omega_{1S}v_R-\frac{\omega_{0S}}{r}) \tag{55}$$

We substitute (55) into (22a) and find the first-order condition of v_R because maximizing (22a) now is (23). Therefore, $v_R^*=v_1$. If $v_1\geq v_2$, we easily verify that v_1 satisfies Constraint (22b) when $P=0$, which proves Part (ii) of Proposition 4. If $v_1<v_2$, P must be positive and $P^*=(\frac{v_0}{v_R^*})^{\beta_S}(I-\Phi_{2S}\omega_{2S}v_R^{*2}-\Phi_{1S}\omega_{1S}v_R^*-\frac{\omega_{0S}}{r})$ to satisfy (22b) when $v_R^*=v_1$, which proves Part (iii) of Proposition 4. □

Proof of Proposition 5:

Use the similar logic as the proof in Proposition 4. □

Proof of Corollary 3:

If $\kappa_S=\kappa_G$, (26) has the same roots as (23), which leads to $v_{RL}^*=v_{RU}^*$. By performing a calculation we know that $(\frac{v_0}{v_{RU}^*})^{\beta_S}\chi^* q_{11} = P^*$ when $v_{RL}^* = v_{RU}^*$, proving the same budget conclusions. □

Appendix C The analysis of the ambiguity-loving case

The analysis of the ambiguity-loving case is similar to the ambiguity-averse case, except for the following: for $\theta_t \in \mathrm{K}_S = [-\kappa_S, \kappa_S]$, we have

$$E_0^\theta[\exp(2\sigma(B_t^\theta - \int_0^t \theta_s ds))] \le E_0^\theta[\exp(2\sigma(B_t^\theta - \int_0^t -\kappa_S ds))] = E_0^\theta[\exp(2\sigma(B_t^\theta + \kappa_S t))] = \exp(2\sigma^2 t + 2\sigma\kappa_S t)$$

$$E_0^\theta[\exp((B_t^\theta - \int_0^t \theta_s ds)\sigma)] \le E_0^\theta[\exp((B_t^\theta - \int_0^t -\kappa_S ds)\sigma)] = E_0^\theta[\exp((B_t^\theta + \kappa_S t)\sigma)] = \exp(\frac{1}{2}\sigma^2 t + \sigma\kappa_S t)$$

Therefore, $\sup_{\theta \in \mathrm{K}_S} E^\theta[\exp(2\sigma(B_t^\theta - \int_0^t \theta_s ds))] = \exp(2\sigma^2 t + 2\sigma\kappa_S t)$ and

$$\sup_{\theta \in \mathrm{K}_S} E^{Q^\theta}[\exp((B_t^\theta - \int_0^t \theta_s ds)\sigma)] = \exp(\frac{1}{2}\sigma^2 t + \sigma\kappa_S t) \tag{56}$$

Using (56) to replace the infinimum operator in the proofs of the ambiguity-averse case with the supremum operator now, we can obtain the results in Section 4.1. □

Appendix D Considering the positive operation costs of the airlines

In this Appendix, we analyze the case that the operation costs of the airlines is not 0. Then, the profit functions of the two airlines are presented as follows:

$$\pi_1 = (p_{11} - c)q_{11} + (p_{12} - f - c)q_{12} \tag{57}$$

$$\pi_2 = (p_2 - f - c)q_2 \tag{58}$$

where c is the marginal operation costs of the airlines, and $c < 1 - f$. To simplify the problem, we assume that their marginal operation costs are the same. Then, the equilibrium outputs of the two airlines in the case without ET are

$$q_2 = q_{12} = \frac{1 - c - f}{2 + b} \tag{59}$$

Airline 1's single-period profit is

$$\pi_1 = \frac{(1 - c - f)^2}{(2 + b)^2} \tag{60}$$

Additionally, the social welfare function in the case without ET becomes

$$u(q_{12}, q_2) = (1 - c)(q_{12} + q_2) - (q_{12}^2 + q_2^2 + 2bq_{12}q_2) / 2 \tag{61}$$

The single-period social welfare in the case without ET is

$$u = \frac{(1 - c - f)[(1 - c + f)b + 3 + f - 3c]}{(2 + b)^2} \tag{62}$$

With the construction of ET, the equilibrium outputs of the two airlines in each period are

$$q_{11} = \frac{(2 - b)[(2 + b)v + (3f + 2c - 2)b + 2 - 2c]}{4(1 - b)(2 + 2b - b^2)} \tag{63}$$

$$q_{12} = \frac{b(b - 4)v + (2 - f - 2c)b^2 + (2f + 6c - 6)b + 4(1 - c - f)}{4(1 - b)(2 + 2b - b^2)} \tag{64}$$

$$q_2 = \frac{-bv - (2 + b)f + 2 - 2c}{4 + 4b - 2b^2} \tag{65}$$

Then, Airline 1's single-period profit increment after the ET construction is

$$\Delta\pi_{1t} = \omega_{2S}v_t^2 + \omega_{1S}v_t + \omega_{0S} \tag{66}$$

where $\omega_{2S} = \dfrac{b^4 - 4b^3 - 4b^2 + 8b + 8}{8(1 - b)(2 + 2b - b^2)^2}$,

$\omega_{1S} = \dfrac{fb^4 + 4(1 - c - 2f)b^3 - 4(2 - 2c - f)b^2 - 4(1 - c - 3f)b + 8(1 - c)}{4(1 - b)(2 + 2b - b^2)^2}$, and

$$\omega_{0S} = \frac{1}{8(1 - b)(4 + 6b - b^3)^2}\{[-4(1 - c)^2 + 8(1 - c)f - 3f^2]b^6 + 8(1 - c)(1 - c - f)b^5 - 4[(1 - c)^2$$
$$-6(1 - c)f + 9f^2]b^4 + 8[4(1 - c)^2 - 13(1 - c)f + 6f^2]b^3 - 8[4(1 - c)^2 + 2(1 - c)f - 9f^2]b^2$$
$$-32(1 - c)(1 - c - 3f)b + 32(1 - c)^2\}$$

We know that $\omega_{2S} > 0$ and $\omega_{1S} > 0$ for all $b \in [0,1)$, $f \in [0,1]$, and $c \in (0,1)$. Because now $\Delta\pi_{1t}$ is still a convex function of v_t, the basic conclusions are the same as in Section 3.3.2, and the operation costs of the airlines is not 0.

In addition, the single-period social welfare increment after the ET construction is

$$\Delta u_t = \omega_{2G} v_t^2 + \omega_{1G} v_t + \omega_{0G} \tag{67}$$

where $\omega_{2G} = \dfrac{3b^4 - 10b^3 - 14b^2 + 24b + 24}{16(1-b)(2+2b-b^2)^2}$,

$\omega_{1G} = \dfrac{(f-4+4c)b^4 + 2(12-5f-12c)b^3 - 2(14-8c-f)b^2 + 8(2c+2f-2)b + 24(1-c)}{8(1-b)(2+2b-b^2)^2}$, and

$$\omega_{0G} = \frac{1}{16(1-b)(4+6b-b^3)^2}[(4-8c+4c^2+8f-8cf-21f^2)b^6 + (42f^2-24f+24cf-16c^2+32c-16)b^5$$
$$+(18f^2+112f-52c^2+104c-112cf-52)b^4 - (96f^2+128f-200c^2+400c-128cf-200)b^3$$
$$-(24f^2+96f+104c^2-208c-96cf+104)b^2 + (128f-128c^2+256c-128cf-128)b + 96(1-c)^2]$$

We know that $\omega_{2G} > 0$ and $\omega_{1G} > 0$ for all $b \in [0,1)$, $f \in [0,1]$, and $c \in (0,1)$. Because Δu_t is now still a convex function of v_t, the basic conclusions are the same as in Section 3.3.3 when the operation costs of the airlines is not 0.

We compare ω_{2S} and ω_{2G}, ω_{1S} and ω_{1G}, and ω_{0S} and ω_{0G} and obtain conclusions similar those in the proof of Proposition 3. Although the detailed parameters' scopes differ, we still have similar qualitative conclusions to those in Section 3.3.4: when the ET investment is not very low (larger than $\min(\frac{\omega_{0S}}{r}, \frac{\omega_{0G}}{r})$), whether their ET investment timing is the same depends on the market competition, the PT charge, and Airline 1's operation costs. If both the government and Airline 1 are ambiguity-averse, and they have the same ambiguity levels, when the competition between the airlines is not very intensive, or the PT charge is not very high, the government prefers an earlier investment than that of Airline 1.