

Unilateral GHG Control Measure and Aviation Industry: A Theoretical Analysis

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Abstract: This paper investigates the effects of unilateral GHG control measures on the aviation industry and total GHG emissions. The result suggests that if a country unilaterally takes actions to control aviation GHG emissions, the charges at its hub and spoke airports may increase. This increase in the airport charges will lead to a shift of domestic connecting flights between hub and spoke airports outside the country. It may also place its home airlines at a strategic disadvantage, as the home airlines usually operate their hubs at the home country. Furthermore, the unilateral control measure will reduce GHG emissions in the country implementing the measure, while it may lead to an increase or a decrease in world emissions. It is because as mentioned, the domestic connecting flights may increase at another country, in which the airline network may be very inefficient in terms of GHG emissions.

JEL classification:

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1. Introduction

Public concerns over climate change have pressured both the aviation industry and regulators to mitigate aviation greenhouse gas (GHG) emissions in hope of avoiding their adverse impacts on global climate. As a result, while a number of airlines set up their own voluntary schemes to reduce their GHG emissions,¹ some governments also consider unilaterally mandating the implementation of some measures to control emissions from the industry. Among these control measures, the one of the largest scale would be the inclusion of the aviation sector in the European Emission Trading System (EU ETS) in 2012.² This kind of unilateral action has been strongly opposed by the industry and various countries, based partly on economic concerns, such as competitive issues.³ For example, Air France argued that the EU ETS would give a competitive edge to those airlines with a hub outside of Europe.⁴ It is because connecting flights between hub and spoke airports in the EU are subject to related GHG charges resulting from the EU GHG emission control measure, while those flights outside the EU are not.

¹ Currently, a number of airlines, including Air Canada, American Airlines, Cathay Pacific, Continental Airlines, Delta Airlines, Northwest Airlines and Qantas, have introduced their carbon offset programs for their customers. More discussion about voluntary emission control measures for aviation can be found in ICAO (2007).

² In July 2008, the European Parliament passed the second reading vote of a directive which includes GHG emissions from flights to, from and within the EU in the EU ETS from 2012. Under the new legislation, all airlines will be covered (irrespective of nationality). They will be able to sell surplus allowances if they reduce their emissions and will need to buy additional allowances if their emissions grow.

³ For example, in the ICAO's meeting in July 2007, the US representative objected to the inclusion of international flights in the EU ETS without their consent, and pointed out that it runs contrary to EU Member State international legal obligations under the Chicago Convention on International Civil Aviation, and under numerous bilateral air services agreements, including those with the U.S.

⁴ Reuters, June 9, 2008.

Due to the potentially significant impacts of unilateral GHG control measures on GHG emissions, national welfare and the aviation industry, the economic arguments for and against the unilateral GHG control measures ought to be examined more rigorously. Although there is a growing empirical literature (e.g., Arthur Anderson, 2001; CE Delft, 2005, 2007; Scheelhaase and Grimme, 2007; Scheelhaase, et al., 2008) examining the effects of GHG control mechanisms in the aviation industry, discussion of the issue so far lacks much relevant theoretical work. Thus this paper aims to provide an analytical framework for investigating GHG emission control measures in the aviation industry. In particular, we will first examine how the unilateral measures affect the competition of airlines with different networks. For example, to serve the same market, airlines may face different GHG charges if their hub locations differ (as argued by Air France mentioned above). Thus the measures may give some airlines strategic advantages in the competition. The empirical results in Scheelhaase, et al. (2008) showed that network carriers based outside the EU are likely to gain a significant competitive advantage, compared to EU network carriers, if the aviation industry is included in the EU ETS. Our second objective is to look at how the unilateral GHG emission control measures affect world emissions and its distribution among countries. In particular, the unilateral measures may affect airlines' pricing and network utilization, which, in turn, could affect world emissions.⁵

⁵ From a different perspective, Hoel (1991) showed that the unilateral reductions of GHG emissions may affect the outcome of international negotiations about reduced emissions, which may imply higher total emissions than if no action is taken.

In the literature, a few theoretical works have been published on pollution control measures on the aviation industry; for example, Brueckner and Girvin (2008) explored the impacts of airport noise regulation on flight frequency and airfares. One of the major differences between this paper and theirs is that we consider asymmetric airlines. In our analysis, two airlines operate flights between two countries, and belong to each country, respectively. Under such duopoly competition, the two airlines use different networks to serve the market. As shown below, the introduction of asymmetry in the analysis is necessary for us to examine the competitive issues and the change in world emissions with the unilateral action to control GHG emissions – the main objectives of this paper. However, due to the complexity after considering the asymmetric case, we cannot take into account flight frequency in our model as the studies in the literature. Yet an important extension to this paper could examine the impacts of GHG control measures on air service quality, such as flight frequency: more frequent flights will reduce scheduled flight delays (Douglas and Miller, 1974). To derive the airlines' demand, we consider an infinite linear city model, where a consumer's utility depends on their brand preference. A number of studies in the literature (e.g., Brueckner and Zhang, 2001; Brueckner, 2004; Brueckner and Flores-Fillol, 2007) consider similar spatial models to examine airlines' network choice between fully-connected (FC) and hub-and-spoke (HS) networks.

In the analysis, we compare the case in which one of the countries unilaterally imposes GHG charges on both airlines with the no-action base case in which both countries have no action regarding GHG emissions. We find that if a country price discriminates between domestic and international flights, the GHG charges may be

positive or negative, while they will be positive when its home airline's profit is not taken into account in the country's airport pricings. On the other hand, under uniform pricing, when a country moves toward GHG pricing, the airport charge will increase. Note that the adverse impacts of the positive GHG charges on the home airline may be larger relative to their foreign counterpart, as the home airline will operate connecting flights between the hub and spoke airports within its home country, where the GHG pricing is implemented. Thus, such an initiative may raise competitive concerns from those airlines. We also show that the positive GHG charges will reduce the total output in the airline market, while domestic flights connecting hub and spoke airports may be shifted from the home country to the foreign counterpart. Nevertheless, the consumer surplus of the air travel market will decrease. Finally, we find that world emissions may increase when a country takes the GHG control actions unilaterally. This is due to the fact that the domestic connecting flights may be shifted to a country with a less efficient network. This is a very interesting result, with potentially important implications for governments deciding to implement unilateral GHG control measures.

The paper is organized as follows: Section 2 discusses the relationship between global climate change and the aviation industry, including GHG control measures implemented in the industry in practice. Section 3 sets up the model, and Section 4 examines airline behavior. Section 5 derives the unilateral GHG pricing, and Section 6 investigates its effects on airline competition, market output, consumer welfare and GHG emissions. Section 7 concludes.

2. Climate Change and Aviation

An increasing amount of scientific evidence indicates that the global climate change is predominantly a result of increases in GHGs caused by human activities (see Stern, 2006, for a comprehensive review). Transportation, in particular, is one of the most important sources of GHG emissions. As with other modes of transportation, air transport produces GHGs during operation. The aviation GHG of most concern is carbon dioxide (CO₂), which has long residence time in the atmosphere. Other aircraft emissions affecting climate include water vapor (H₂O), nitrous oxide (NO_x), sulphate (SO₄) and soot particles. Currently, the aviation industry contributes 3 percent of the total man-made contribution to climate change (IPCC, 2007). Given the fact that the direct contribution of the industry to the global gross domestic product (GDP) is only about 1 percent, the industry share of the man-made contribution to climate change is thus significant. Furthermore, air travel grew significantly in the past decade and will continue growing at a rapid pace in the coming years. This rapid growth in air traffic may lead to a significant increase in GHG emissions from the sector, even with improvements in aircraft fuel efficiency.⁶ IPCC (2007) found that CO₂ emissions from global aviation increased by a factor of about 1.5 from 1990 to 2000, and predicted that the emissions will continue to grow by around 3-4 percent each year, unless additional measures are taken; Olsthoorn (2001) estimated that between 1995 and 2050, aviation emissions of CO₂ may increase by a factor of 3-6.

⁶ IPCC (2007) forecasted that technology developments might offer only a 40-50 percent improvement in fuel efficiency over 1997 level by 2050, while air traffic growth is estimated to be around 5 percent each year.

Given its global character, it is sensible for countries to act collectively to control GHG emissions. As of May 2008, more than 180 countries have signed and ratified the Kyoto Protocol,⁷ an international agreement that sets binding targets for countries and regions to reduce GHG emissions. Yet, while the Protocol accounts for domestic aviation emissions, emissions from international aviation are not included.⁸ It may be because allocating international aviation emissions to specific countries may be difficult. Instead, the Protocol calls for countries to pursue limitation or reduction of GHG emissions from international flights through the International Civil Aviation Organization (ICAO).⁹ Currently, the ICAO focuses mainly on technological and operational measures in GHG emission control, whereas the progress of market-based measures through the organization is still limited.¹⁰ Instead, a number of airlines set up their own voluntary schemes, in which passengers can pay extra to offset their emissions. The revenues from the passengers are then spent on various offset programs. Hodgkinson, et al. (2007) argued that the schemes do serve a useful purpose in enabling passengers who are concerned about their emissions to make an essentially carbon neutral flight. On the other hand, British Airways voluntarily participated in the UK ETS to reduce their emissions of CO₂ equivalent to below set targets. In return, it received an incentive payment from the UK Government. However, the effectiveness of those voluntary measures is still questionable.

⁷ The participating countries now contribute to about 64 percent of global GHG emissions in total.

⁸ Annex I Parties of the Protocol.

⁹ Article 2.2 of the Protocol.

¹⁰ In particular, the ICAO has decided not to work towards a new global legal market-based instrument under the organization in 2004.

As a result, some governments are also considering unilaterally mandating some measures to control emissions from the aviation industry. A growing number of empirical studies have been conducted to evaluate the proposed measures. Scheelhaase and Grimme (2007) provided an empirical estimation of the impacts of the inclusion of the aviation sector in the EU ETS on operating costs and transport demand for full service and low cost airlines, and found that the financial impact on low cost carriers and regional airlines is likely to be significantly greater than for network carriers. Furthermore, Scheelhaase, et al. (2008) found that EU network carriers are likely to encounter competitive disadvantages compared to airlines from non-EU countries on long-haul flights. Benito (2008) estimated the aviation CO₂ emissions reduction with the proposed EU ETS by taking into account the substitution between air travel and high-speed railways in the EU. In addition to the EU ETS mentioned above, the UK government levies an “Air Passenger Duty,” which is designed to reduce CO₂, on all airline tickets sold in the country. However, IATA (2006) opposed the levy because the climate benefits due to the reduction in emissions is estimated to be £53 million only, while the GDP losses would be £400 million plus losses to air travelers. Hofer, et al. (2008) investigated the effects of an air travel carbon emissions tax on total travel-related carbon emissions in the U.S. They highlighted the fact that emissions taxes on air travel may cause potentially significant air-to-automobile diversion effects, which may substantially reduce the environmental benefits of air travel carbon emissions taxes. Forsyth (2008), and Forsyth and Ho (2008) discussed the Australian ETS by taking direct emissions from aviation and indirect emissions from other industries, such as tourism, into account.

3. The Model

This analysis considers a model with an airline in country H (i.e., airline H) and an airline in country F (i.e., airline F) serving a same origin-destination (OD) market. As depicted in Figure 1, a simple air transport network is considered, as this is likely the simplest structure allowing us to address the main questions concerning us. To simplify the analysis, we focus on the OD market between airports H and F (i.e., the spoke airports in countries H and F, respectively). To serve the market, each airline will bring their passengers from the origin to its hub, which is located at its respective country (i.e., airports A and B for airlines H and F, respectively), and then from the hub to the destination. In practice, it is very common for airlines operating HS networks in both their domestic and international markets after market deregulation in the aviation industry (see Zhang, et al., 2008, for a review). One example relevant for our analysis is the air travel market between Vancouver and Munich. In this market, Air Canada will take up passengers from Vancouver and fly to Toronto, which is Air Canada's hub for its transatlantic market, then from Toronto to Munich. On the other hand, Lufthansa serves the market by connecting at Frankfurt. The assumption that airlines choose (or are only allowed to use) airports at their home country as their hubs can be justified for at least two reasons. First, although the international aviation market has been moving toward greater liberalization, cabotage is usually prohibited, and thus airlines are restricted to

operate flights within the domestic borders of another country.¹¹ Second, most major airports around the world are suffering from congestion. Home carriers usually dominate those airports, implying that foreign carriers with limited access to the airport facilities may have difficulties operating their own flights at those airports.¹²

[Figure 1 here]

In the model, aircrafts emit GHGs during the flight, where the emission intensity (i.e., emissions per flight between two airports) depends on the route they fly. On the other hand, for simplicity, we will abstract from other possible OD markets in the network (e.g., H to B, A to H) in our analysis.¹³ The stylized problem that we want to analyze is the following: when one of the countries adopts (unilateral) GHG pricing, what are its effects on airlines' operating decisions, competition, market output, consumer benefits and world emissions? We model the problem as a two-stage game. In the first stage, countries determine the charges, with part of them owing to GHG pricing, at their respective hub and spoke airports. In the second stage, the two airlines compete in Cournot fashion.¹⁴

¹¹ A few exceptions include the creation of single aviation markets in the EU, and between Australia and New Zealand, in which cabotage rights are granted to airlines in the markets.

¹² Ciliberto and Williams (2007) measured the importance of operating barriers to entry, including limited access to airport facilities, as determinants of the hub premium; they found that exclusive access to and dominance of gates at the market endpoint airports are key determinants of the hub premium.

¹³ Under this simplification, our model will not take the advantages of HS network into account, including those due to demand and cost complementarities, which have been widely discussed in the literature (e.g., Oum, et al., 1995; Hendricks, et al., 1995, 1999; Brueckner and Zhang, 2001; Brueckner, 2004; Brueckner and Flores-Fillo, 2007).

¹⁴ Cournot competition between air carriers has been a common assumption in the theoretical airport pricing literature, which in fact has some empirical backing (e.g., Brander and Zhang, 1990; Oum, et al., 1993). See Basso and Zhang (2007b) for a review of the airport pricing literature.

To derive the demand faced by the two airlines, we specify and solve the consumers' problem as follows. We consider an infinite linear city, where potential consumers are distributed uniformly with a density of one consumer per unit of length. Basso and Zhang (2007a) use a similar spatial model to investigate the rivalry between congestible facilities. Airlines F and H are located at 0 and 1, respectively, and the locations of the airlines are exogenous. If a consumer located at z chooses to travel by F, then she derives a net benefit (utility):

$$U_F = V - p_F - 4\tau|z|, \quad (1)$$

where V is the gross travel benefit; p_F is the (equilibrium) airline F's airfare; 4τ is a parameter capturing consumers' transportation cost (i.e., the intensity of consumers' brand preference to airlines: consumers located closer to an airline's location will enjoy a higher benefit than others if they fly by that airline, given the same airfare), and τ is assumed to be positive.¹⁵ Similarly, if the consumer chooses to travel by H, then she derives a net benefit (utility):

$$U_H = V - p_H - 4\tau|1 - z|, \quad (2)$$

where p_H is the (equilibrium) airline H's airfare.

¹⁵ This transportation cost is multiplied by 4 in order to simplify most of the equations in the paper (see, e.g., equations (6)).

Assuming that everyone with $z \in [0,1]$ travels and both airlines capture some of the travelers,¹⁶ then the consumer with \tilde{z} will be indifferent between the two airlines when (also see Figure 2):

$$V - p_F - 4\tau\tilde{z} = V - p_H - 4\tau(1 - \tilde{z}),$$

or when

$$\tilde{z} = \frac{1}{2} + \frac{p_H - p_F}{8\tau}. \quad (3)$$

[Figure 2 here]

Condition (3) suggests that, when the airline H's (airline F's) fare decreases, more (less) passengers will choose airline H rather than airline F. Furthermore, airlines F and H serve consumers with $z < 0$ and $z > 1$, respectively. The cutoff points z^l and z^r for the customers between travel with airlines F and H, respectively, and not travel by air (which utility is normalized to zero) can be derived as follows:¹⁷

¹⁶ To have everyone with $z \in [0,1]$ travel, we assume $2V \geq p_H + p_F + 4\tau$, and to have both airlines capture some of the travelers, we assume $|p_H - p_F| < 4\tau$. Both of which are our maintained assumptions in the following analysis.

¹⁷ The “no travel by air” option may also include traveling by other modes of transportation, such as automobile and high-speed railways. In such cases, we may need to further consider the consumer benefits and emissions from other modes of transportation in the following analysis. This kind of diversion effects are empirically examined in Benito (2008) and Hofer, et al. (2008).

$$z^l = -\frac{V - p_F}{4\tau}, \quad z^r = 1 + \frac{V - p_H}{4\tau}. \quad (4)$$

By conditions (3) and (4), we can derive the demand system as follows:

$$q_F = \frac{V + 2\tau}{4\tau} + \frac{p_H - 3p_F}{8\tau},$$

$$q_H = \frac{V + 2\tau}{4\tau} + \frac{p_F - 3p_H}{8\tau}. \quad (5)$$

For simplicity, q_i is measured by the number of flights. This measurement is equivalent to the number of passengers if each flight has an equal number of passengers, which holds when all flights use identical aircraft and have the same load factor. Note from (5) that an airline loses traffic when its fare rises, while it gains traffic when another airline's fare rises. In other words, the service provided by an airline is a substitute to another. From the demand system (5), we can obtain the following inverse demand functions faced by the two airlines:

$$p_F(q_H, q_F) = 2\tau + V - 3\tau q_F - \tau q_H,$$

$$p_H(q_F, q_H) = 2\tau + V - 3\tau q_H - \tau q_F. \quad (6)$$

The inverse demand system (6) will be used to solve the Cournot-Nash equilibrium in Section 4.

4. Airline Competition

We shall examine the subgame perfect equilibrium of the two-stage game, starting with the analysis of the airlines' subgame in the second stage. Having characterized the demands in Section 3, we now specify airlines' cost. The carriers are symmetric in the sense that they have the same cost function. The airline i 's total cost function is given as:

$$C_i(q_i) = (c + t_i^S + t_i^U + t_{-i}^S)q_i, \quad (7)$$

where c is the (constant) marginal cost per flight.¹⁸ Recall that an airline will fly from a spoke airport to another spoke airport through the hub located at its home country. As a result, airline i will incur per-flight charges at the home country's spoke and hub airports, t_i^S and t_i^U , respectively, and a per-flight charge at the foreign country's spoke airport, t_{-i}^S . The airport charges will be determined in Section 5. In our analysis, we assume that the per-flight aircraft emissions in each route are exogenous.¹⁹ Furthermore, the GHG taxes considered in Section 5 depend only on airlines' output. Thus, there is no incentive for airlines to improve their efficiency in GHG emissions. As a result, the GHG abatement

¹⁸ Here, we assume that the airlines are operating under constant returns to scale. By using different cost functions, Kumbhakar (1990, 1992) and Hansen, et al. (2001) empirically found that airlines operate under increasing returns to scale, while Caves, et al. (1984) and Chua, et al. (2005) found constant returns to scale.

¹⁹ In practice, some airlines have made some progress in GHG emission control. For example, Air Canada reduced the emission intensity of its flight operations by 28 percent since 1990 by investing in energy efficient new aircrafts, including Embraer regional jets and Boeing 777s.

cost is not included in (7). Yet an interesting extension to the present analysis would be considering incentive mechanisms for airlines to improve their emission intensity.

In the second stage, airline i chooses the number of flights to maximize its own profit. Thus its optimization problem is:

$$\begin{aligned} \text{Max}_{q_i} \pi_i(q_i; q_{-i}) &= p_i q_i - C_i(q_i) && (\text{for } i = F, H) \quad (8) \\ &= (2\tau + V - 3\tau q_i - \tau q_{-i})q_i - (c + t_i^S + t_i^U + t_{-i}^S)q_i. \end{aligned}$$

The first-order condition for the maximization problem is:

$$\frac{\partial \pi_i}{\partial q_i} = (2\tau + V - 6\tau q_i - \tau q_{-i}) - (c + t_i^S + t_i^U + t_{-i}^S) = 0, \quad (\text{for } i = F, H) \quad (9)$$

where $\partial^2 \pi_i / \partial q_i^2 = -6\tau < 0$. Thus, the second-order condition holds.

Solving equations (9), the airline i 's equilibrium output is:

$$q_i = \frac{2\tau + V - c - t_i^S - t_{-i}^S}{7} - \frac{6t_i^U - t_{-i}^U}{35}. \quad (\text{for } i = F, H) \quad (10)$$

Conditions (10) suggest that airline i 's output decreases in the charges at the home country's airports (both the hub and spoke airports) and the foreign country's spoke airport, while it increases in the foreign country's hub airport charge. Furthermore, the total market output, $Q = q_i + q_{-i} = [2(2\tau + V - c - t_i^S - t_{-i}^S) - (t_i^U + t_{-i}^U)]/7$, decreases in the hub and spoke airport charges at both home and foreign countries.

Substituting (10) into (6), the equilibrium prices are:

$$p_H(q_F, q_H) = (2\tau + V)\left(1 - \frac{4}{7}\tau\right) + \frac{\tau}{35}[20(c + t_H^S + t_F^S) + 17t_H^U + 3t_F^U], \quad (11)$$

$$p_F(q_H, q_F) = (2\tau + V)\left(1 - \frac{4}{7}\tau\right) + \frac{\tau}{35}[20(c + t_H^S + t_F^S) + 17t_F^U + 3t_H^U]. \quad (12)$$

5. Country Stage

To examine the effects of the unilateral GHG emission control measure, we first derive the optimal airport charges, with part of them owing to GHG pricing. In this paper, we focus on the unilateral action from a country to control GHG emissions. Thus, in the country stage, we consider country H chooses charges t_H^U and t_H^S at its hub and spoke airports, respectively, taking the subsequent carriers behavior into account. The airport charges at country F are assumed to be exogenous.²⁰ Country H will maximize the following welfare function:

²⁰ If both countries' airport pricings are treated as endogenous, we need to consider the strategic behaviors between the two countries (see Yuen, Basso and Zhang, 2008, Small and Verhoef, 2007, and

$$\underset{t_H^S, t_H^U}{Max} SW_H = \alpha CS + \beta \pi_H + TR_H - \gamma E_H, \quad (13)$$

where CS is total consumer surplus of the air travel market. α and β , which are positive, capture the importance (relative to tax revenue) of consumer surplus and home airline's profit, respectively, in country H's policy-making decision.²¹ TR_H is country H's tax revenue, which is the sum of tax revenues from its spoke and hub airports (i.e., $t_H^S(q_H + q_F)$ and $t_H^U q_H$, respectively). Recall airline H will use both the hub and spoke airports at country H, while airline F will only use the spoke airport at the country (see Figure 1). E_H is the GHG emissions related to country H, the positive γ is the country H's GHG (per-unit) abatement cost or the cost to meet a GHG control target, for example, those set under the Kyoto Protocol.²² Thus, the last term in (13) is the total cost on GHG emission reduction in order to meet a particular emission target. Note that the last term in (13) may also be interpreted as the benefits of emission reduction to the country and its consumers. In particular, for $\gamma = 0$, country H does not account for any GHG emission costs to the country. Thus, the pricing derived from the maximization problem in (13)

Ubbels and Verhoef, 2008, for recent reviews of the studies on the strategic behaviors of transport facilities).

²¹ The magnitudes of α and β depend on a number of factors, including the percentage of foreign ownership stake in the home airline, the proportion of consumers from country H relative to the whole air travel market, costs of taxation from other sectors, etc. For example, in case of France, which supports national "champion" such as Air France, β tends to be large.

²² For example, a country may offset its GHG emissions through some project-based transactions, in which the buyer purchases emission credits from a project that can verifiably demonstrate GHG emission reductions compared with what would have happened otherwise. The most notable examples of such activities are under the Clean Development Mechanism (CDM) and the Joint Implementation (JI) mechanisms of the Kyoto Protocol. In 2006, the CDM and JI grew sharply to a value of about US\$5 billion (World Bank, 2007).

will not include any GHG component – the base case considered in this paper. In the following, we will compare the equilibrium in the base case with that in the case of $\gamma > 0$.

We further specify the GHG emissions related to country H as follows:

$$E_H = e_H q_H + \delta e_K (q_H + q_F), \quad (14)$$

where e_H and e_K are the (per-flight) emissions of domestic travel in country H (i.e., between A and H as shown in Figure 1) and international travel (i.e., between A and F or between B and H), respectively. In practice, the emissions depend on a number of factors, including aircraft type, load factor and flight distance. In our present analysis, those factors are treated as given, thus the per-flight emissions are exogenous. Yet it is an important extension for this paper to consider the factors endogenously in the analysis. More details about this extension will be discussed in the concluding remarks of this paper. On the other hand, the international emissions are discounted by a factor $\delta \in [0,1]$ in counting the emissions related to country H. The different weight of domestic and international emissions in counting the emissions related to country H may be due to different treatments between the two kinds of flights in the existing GHG control mechanisms. For example, as mentioned, emissions from domestic flights are included in the Kyoto Protocol, while those from international flights are not.

An important assumption here is that country H will not take the emissions of domestic flights of another country into account. Note that although GHG emissions may

have global effects, GHG emission control measures considered by most countries in practice aim to limit the emissions within its own territory, rather than global emissions. For example, under the EU ETS, the EU Member States are required to limit their emissions below *national* emission caps. On the other hand, in evaluating the effectiveness of the inclusion of the aviation sector in the EU ETS, the Full Assessment Report (EC, 2006) submitted by the European Commission only took into account the emissions from flights to, from and within the EU, but not from the flights outside the EU. Similarly, CE Delft (2005), a report commissioned by the European Commission, also evaluated different GHG control options by comparing the emissions from the flights within the European airspace.

In the following, we will explore both the price discrimination case and the “uniform pricing” case, in which country H charges a uniform (per-unit) charge to flights at its hub and spoke airports. Note that the uniform pricing case does not necessarily mean flights at the hub and spoke airports are charged exactly the same taxes. Instead, it should be understood as the existence of some *a priori* rule which says that flights at the hub and spoke airports are charged according to some fixed ratio (for example, the hub airport charges three times what the spoke airport charges). To save on notation – but without losing insight – we set the ratio to one in the uniform pricing case, that is, $t_H^S = t_H^U = \bar{t}_H$. In practice, the uniform pricing case in our analysis may be more relevant. For example, the proposal for including the aviation sector in the EU ETS requires domestic and international flights to participate in the same ETS. As a result, the flights

are required to buy emission permits from the ETS at a same price. Nevertheless, both the price discrimination case and the uniform pricing case will be examined in the following.

In the price discrimination case, country H chooses airport taxes at its hub and spoke airports to maximize its social welfare given in (13). The first-order conditions with respect to the charges give rise to the welfare-maximizing pricing rules. We obtain (the derivation is straightforward but long, and is hence given in Appendix):

$$t_H^U = \left\{ \frac{5[14 - \beta + \tau(\beta - 4\alpha)]}{\Omega_1} e_H + \frac{30(2 - \tau)\beta\delta}{\Omega_1} e_K \right\} \gamma + K_1, \quad (15)$$

$$t_H^S = \left\{ \frac{6\beta + 17\alpha\tau - 6\beta\tau}{\Omega_1} e_H + \frac{[70 - 65\beta + (29\beta + 14\alpha)\tau]\delta}{\Omega_1} e_K \right\} \gamma + K_2, \quad (16)$$

where $\Omega_1 = -(\tau - 1)^2 \beta^2 + 2(34\tau + 3\alpha\tau - 70)\beta - 4(2\alpha\tau + 3)\alpha\tau + 140 > 0$ by the second-order conditions. K_1 and K_2 are constants.

In the base case, country H does not take the GHG emission cost into account, i.e., $\gamma = 0$. Thus, equations (15) and (16) suggest that in the base case, the equilibrium charges at the hub and spoke airports at country H are equal to K_1 and K_2 , respectively. In particular, K_1 and K_2 may be considered as trade taxes (or subsidies) under imperfect international competition, which have been widely discussed in the strategic trade policy literature (e.g., see Brander, 1995, for a comprehensive review). When country H moves toward (unilateral) GHG pricing (i.e., $\gamma > 0$), the bracketed terms in (15) and (16)

(multiplied by a positive γ) are those additional components to the base case. An interesting catch here is that, once GHG emissions are taken into account, the airport charges may increase or decrease. This result seems contradictory to the traditional wisdom that a positive charge should be imposed to internalize the negative externality (e.g., pollution or GHG emissions in our case). To understand why the signs of the additional terms are undetermined, we make note of three points. First, an increase in airport charges may decrease the airlines' output, thereby reducing GHG emissions. Second, an increase in t_H^U , which is only imposed on airline H, may shift customers to airline F. Thus domestic connecting flights in country H decrease, while those in country F increase. Recall that only the emissions from the former are counted in country H's emissions, but not that from the latter. As a result, the emissions related to country H may decrease. Third, a decrease in airport charges may confer a strategic advantage to its home airline. Note that the home airline will use both the hub and spoke airports, while its foreign counterpart will only use the spoke airport. Thus, the decrease in the airport charges will benefit the home airline more than its foreign counterpart. While the first two have positive effects on the airport charges after GHG emissions are taken into account, the last effect implies that negative GHG charges are possible.

To see how the airline H's profit in (13) affects the airport charges after the unilateral GHG taxes are imposed, we consider a particular case that country H does not take airline H's profit into account (i.e., $\beta = 0$). As a result, the last effect discussed above vanishes. In this case, equations (15) and (16) reduce to:

$$t_H^U = \frac{5e_H}{2(\alpha\tau + 5)}\gamma + K_4 > 0, \quad (17)$$

$$t_H^S = \frac{1}{(7 - 2\alpha\tau)} \left[\frac{17\alpha\tau}{(\alpha\tau + 5)} e_H + 14\delta e_K \right] \gamma + K_3 > 0, \quad (18)$$

where the denominators are positive by the second-order conditions. K_3 and K_4 are constants. Equations (17) and (18) suggest that, when country H does not take airline H's profit into account, both the airport charges at the hub and spoke airports will increase, after country H implements GHG pricing. Note that the GHG taxes are increasing in γ . In other words, as the GHG abatement cost increases, country H will charge higher taxes on flights. Equations (17) and (18) show that the charge at the spoke airport increases in both e_H and e_K , while the charge at the hub airport increases only in e_H . This observation implies that the two charges serve different roles in the GHG control. Recall that only airline H will be subject to t_H^U . Thus, an increase in t_H^U will decrease the output by airline H, thereby reducing the emissions from the domestic flights in country H. As a result, if the domestic flights in country H are less efficient in GHG emission (a large e_H), a higher t_H^U is necessary. Note that an increase in t_H^U will also increase the output by airline F, thereby increasing the emissions from the domestic flights in country F, though country H does not take this into account. On the other hand, an increase in t_H^S will reduce the output of both airlines, thereby reducing both the emissions from the domestic flights in country H and international flights operated by the two airlines. Thus, t_H^S increases in both e_H and e_K . The above discussion leads to:

Proposition 1 In the price discrimination case, when a country moves toward GHG pricing, its airport charges may increase or decrease, while the charges will increase if the country does not take its airline's profit into account.

We next consider the uniform pricing case, in which country H chooses a single airport tax at the hub and spoke airports (i.e., $t_H^S = t_H^U = \bar{t}_H$) to maximize its social welfare given in (13). The first-order condition with respect to the charge gives rise to the welfare-maximizing pricing rules. We obtain (see the derivation in Appendix):

$$\bar{t}_H = \frac{35}{\Omega_2} (11e_H + 15\delta e_K)\gamma + K_5, \quad (19)$$

where $\Omega_2 = -401\alpha\tau + 814\beta\tau - 1540\beta + 1820 > 0$ by the second-order condition. K_5 is a constant.

Equation (19) suggests that when country H moves toward GHG pricing (i.e., from $\gamma = 0$ to $\gamma > 0$), the (single) airport charge will increase. The airport charge is a weighted average of e_H and e_K . The weight of e_K depends on δ , the discount factor of the international emissions in counting country H's GHG emissions. Note that for $\delta = 1$, the weight of e_H is less than that of e_K in the airport charge given in (19). This result may be due to the existence of a trade-off in country H's airport pricing between domestic emission reduction in country H and airline H's profit. In particular, a measure to reduce the domestic emissions, which are only from the flights operated by airline H,

will increase airline H's operating cost, but have no effect on that for airline F. As a result, this will confer a strategic advantage to airline F. Yet this tradeoff does not exist in a measure to reduce the international emissions, as it affects both airlines' operating cost by the same amount. As a result, for $\delta = 1$, country H may have more incentives to reduce the international emissions than domestic ones. Finally, it is important to note that, with uniform pricing, the effects of the GHG measure on airline H will be larger than that on airline F. This is due to the fact that airline H will be subject to the airport charge at both the hub and spoke airports in country H, while airline F will only incur such charge at the spoke airport but not at the hub airport in country H. As equation (19) suggests that the airport charge will increase after the imposition of GHG pricing, the pricing may confer a strategic advantage to airline F in the competition. As a result, the GHG pricing may raise competitive concerns. This leads to the following proposition:

Proposition 2 In the uniform pricing case, when a country moves toward GHG pricing, its airport charge will increase, which will place its airline at a strategic disadvantage.

Before analyzing how the unilateral GHG pricing affects the airline competition and total emissions, it is important to note that the results in this section may have significant implications for empirical studies on the issue. We show that the implementation of the GHG pricing may have different impacts on home and foreign airlines. As a result, the pricing may alter the strategic relationship between the home and foreign airlines. If this effect is not taken into account in the empirical studies on the issue, the estimation in those studies may underestimate the effects of the GHG pricing

on the welfare of the country implementing the measures and its airlines' profits. On the other hand, the empirical studies may overestimate the effects on consumers, as it does not account for their option to choose an airline less affected by the GHG control measures.

6. Effects of Unilateral GHG Pricing

In this section, we further investigate the effects of unilateral GHG pricing examined in the previous section on market outputs, consumer surplus and GHG emissions. We focus on two particular cases: the price discrimination case in which airline H's profit is not taken into account in country H's airport pricings (i.e., $\beta = 0$) and the uniform pricing case. Note that as the change of airport charges in the general price discrimination case is undetermined as shown in the previous section, its effects on market outputs and emissions are also generally undetermined.

6.1 Market outputs and consumer surplus

For the price discrimination case with $\beta = 0$, substituting equations (17) and (18) into (10) gives the following expressions for the changes in market outputs under unilateral GHG pricing (superscripts A and B for variables after and before the imposition of the unilateral GHG pricing, respectively):

$$q_H^A - q_H^B = -\frac{\gamma[(12 - \alpha\tau)e_H + 2(5 + \alpha\tau)\delta e_K]}{4(\alpha\tau + 5)(7 - 2\alpha\tau)} < 0, \quad (20)$$

$$q_F^A - q_F^B = -\frac{\gamma[(2 - 3\alpha\tau)e_H + 2(5 + \alpha\tau)\delta e_K]}{4(\alpha\tau + 5)(7 - 2\alpha\tau)} < or > 0, \quad (21)$$

$$Q^A - Q^B = -\frac{\gamma(e_H + 2\delta e_K)}{2(7 - 2\alpha\tau)} < 0, \quad (22)$$

where the denominators are positive by the second-order conditions for country H's welfare maximization problem.

Equation (20) suggests that airline H's output will decrease after the imposition of unilateral GHG pricing. After the policy change, both airline H and F's (equilibrium) fares will increase, while the increase for the former will be more than that for the latter (see equations (11) and (12)). Given this, we can break down the decrease in airline H's output into two parts (also see Figure 3): (i) an increase in airport charges will increase the fare charged by airline H, and lead to a contraction of airline H's market at the region where consumers located at $z > 1$ (i.e., z^r decreases); (ii) the airline H's market share in the market for consumers with z between 0 and 1 will decrease (i.e., \tilde{z} increases). As mentioned, an increase in airport charges will have a stronger (positive) effect on airline H's fare than that on airline F's fare. Thus, more consumers in the region of $0 \leq z \leq 1$ will choose airline F over airline H. Equation (21) suggests that the airline F's output may increase or decrease. The result is undetermined because airline F's market at the region

where consumers located at $z < 0$ will contract (i.e., $|z'|$ decreases), while its market share in the market for $0 \leq z \leq 1$ will increase.

[Figure 3 here]

Nevertheless, equation (22) suggests that the total market output will decrease after the imposition of the unilateral GHG pricing. Note that as the market size in the region of $0 \leq z \leq 1$ does not change, the decrease in the total market output is due to the decrease in the market at the two extremes (i.e., $z < 0$ and $z > 1$). On the other hand, we can conclude that consumer surplus of the air travel market will decrease after the imposition of the unilateral GHG pricing. It is because, on one hand, fewer consumers will choose to travel by air (i.e., Q decreases). On the other hand, passengers traveling on both airlines H and F will face higher fares. This result suggests that it is important to consider the adverse impact on consumer benefits, when a country plans to implement GHG control measures.

Proposition 3 In the price discrimination case, when a country moves toward GHG pricing without taking its airline's profit into account, its airlines' and total market outputs will decrease, while that of the foreign airline may increase or decrease. Consumer surplus will decrease.

For the uniform pricing case, by substituting equation (19) into (10), the changes in market outputs under the unilateral GHG pricing are given below:

$$q_H^A - q_H^B = -\frac{11(11e_H + 15\delta e_K)\gamma}{\Omega_2} < 0, \quad (23)$$

$$q_F^A - q_F^B = -\frac{4(11e_H + 15\delta e_K)\gamma}{\Omega_2} < 0, \quad (24)$$

$$Q^A - Q^B = -\frac{15(11e_H + 15\delta e_K)\gamma}{\Omega_2} < 0. \quad (25)$$

Equations (23) to (25) suggest that the total market output, and airline H and F's outputs will decrease after country H implements GHG pricing. Comparing (23) and (24), we can see that the decrease in airline H's output will be greater than that for airline F's output. This is due to fact that airline H will be charged twice (at the hub and spoke airports in country H) by the expression given in (18), while airline F will be charged once (at the spoke airport in country H). Thus, the airline H's fare will increase more than that for airline F's fare. As a result, airline H's market share in the market for $0 \leq z \leq 1$ will decrease (i.e., \tilde{z} increases). On the other hand, as in the price discrimination case, the decrease in total market output in (25) is due to the decrease in the market at the two extremes (i.e., $z < 0$ and $z > 1$). For the consumer surplus, since airfares increase and output decreases, consumers will be worse off after the imposition of unilateral GHG pricing.

Proposition 4 In the uniform pricing case, when a country moves toward GHG pricing, both its home and foreign airlines' outputs will decrease, and consumer surplus will decrease.

6.2 GHG emission

In this section, we examine how the unilateral GHG control measure will affect world emissions. This section may be related to the pollution haven hypothesis discussed in the environmental economics literature (see, e.g., Copeland and Taylor, 1994), which suggests that industries that are highly (local) pollution-intensive may migrate from high-income countries to its low-income counterparts, causing world pollution to increase.²³ Yet note that the effect of GHG emissions is global: its impact is independent of where in the world the emissions occur. In the following, we will explore a possibility that the aviation GHG emissions may be shifted from a country to another, which may lead to an increase in world emissions. As in the previous section, we focus particularly on the price discrimination case, in which airline H's profit is not taken into account in country H's airport pricings (i.e., $\beta = 0$) and on the uniform pricing case. The world emissions are the sum of the emissions from airlines H and F, thus:

$$E = q_H (e_H + e_K) + q_F (e_F + e_K), \quad (26)$$

where e_F is the (per-unit) emissions due to the connecting flights operated by airline F between the hub and spoke airports in country F (i.e., the route between B and F as shown in Figure 1). Thus, the first term on the RHS of (26) is the total emissions from airline H's flights, and the second term is those from airline F's flights. Note that

²³ Empirical studies of the pollution haven hypothesis can be found in, for example, Grossman and Krueger (1991), Xu (2000), Eskeland and Harrison (2003), Kahn (2003), Levinson and Taylor (2004), and Ederington, et al. (2005).

domestic flights in a country with a lower e_i are more efficient in terms of GHG emission than that in another country. Thus, the difference between e_H and e_F may capture the difference of factors affecting emission intensity of domestic routes in countries H and F, including aircraft fuel efficiency, route structure and load factor.

For the price discrimination case with $\beta = 0$, by substituting equations (20) and (21) into (26), and rearranging the equation gives:

$$\begin{aligned}
 & E^A - E^B \\
 &= -\frac{\gamma[(12 - \alpha\tau)e_H + 2(5 + \alpha\tau)\delta e_K]}{4(\alpha\tau + 5)(7 - 2\alpha\tau)}e_H - \frac{\gamma(e_H + 2\delta e_K)}{2(7 - 2\alpha\tau)}e_K - \frac{\gamma[(2 - 3\alpha\tau)e_H + 2(5 + \alpha\tau)\delta e_K]}{4(\alpha\tau + 5)(7 - 2\alpha\tau)}e_F
 \end{aligned}
 \tag{27}$$

Equation (27) suggests that the total GHG emissions may increase or decrease after the imposition of unilateral GHG pricing. It is a very interesting result. To deal with the GHG problem, many environmental groups advocate that given the absence of an international agreement, a country ought to take unilateral actions to reduce its environmentally harmful emissions, as they at least contribute in the right direction (Hoel, 1991). Yet here we show that a country's unilateral action may possibly worsen the problem rather than improve it. To understand the intuition behind the result, we need to further examine the factors affecting the sign of world emission change. From equation (27), it can be shown that:

$$E^A - E^B > 0$$

$$\text{if and only if (i) } e_F > \frac{(12 - \alpha\tau)e_H^2 + (5 + \alpha\tau)[2e_H(\delta + 1) + 4e_K\gamma]e_K}{(3\alpha\tau - 2)e_H - 2(5 + \alpha\tau)\delta e_K},$$

$$\text{and (ii) } (2 - 3\alpha\tau)e_H + 2(5 + \alpha\tau)\delta e_K < 0. \quad (28)$$

Condition (28) suggests that total GHG emissions will increase after the imposition of the unilateral GHG pricing, if and only if the (per-flight) emissions for the domestic flights in country F (i.e., e_F) is larger than a threshold (i.e., (i) in (28) holds) and the domestic flights in country F increases after country H implements the GHG pricing (it would be the case when (ii) in (28) holds, see equation (21)). In Proposition 3, we find that domestic flights in country H and total output will decrease after imposing the GHG pricing, while the domestic flights in country F may increase. Thus, the emissions from domestic flights in country H and international flights will decrease, while that in country F may increase. These two opposing effects on total emissions depend on the emission intensity of the three routes. When e_F is very large, the latter effect may dominate. In other words, the unilateral GHG pricing may result in a shift of domestic flights from one country to another, which may have a less efficient domestic network. As a result, the unilateral GHG pricing may increase world emissions. Although this paper does not explicitly consider global cooperation in control measures, the potential adverse impact of the unilateral GHG control action on world emissions control may provide an argument to support international cooperation on the issue.

Proposition 5 In the price discrimination case, when a country moves toward GHG pricing, total emissions may increase or decrease, depending on aircrafts' emission efficiency in that country and its foreign counterparts.

Proposition 5 may have significant implications for implementing GHG control measures unilaterally, like the inclusion of the aviation industry in the EU ETS. As EU airlines operating flights between EU airports may face a stricter regulation on GHG emissions (i.e., need to buy permits for their emissions), they may be required to charge a higher fare to their customers. As a result, more consumers may choose non-EU airlines, and thereby increasing hubbing activities outside the EU. For example, after the inclusion of the aviation sector in the EU ETS, it is expected that more domestic connecting flights in the EU for hubbing will be shifted to the U.S., as US airlines, which usually operate their hubs in the U.S., may gain a larger market share of the transatlantic market (Scheelhaase, et al. 2008). On the other hand, Table 1 shows the emission intensity of domestic flights in some selected routes in the U.S. and the EU. It suggests that the US domestic flights are less efficient than that in the EU in terms of GHG emissions. Thus, to evaluate the effectiveness of the inclusion of the aviation industry in the EU ETS, it is important to take the change in GHG emissions outside the EU into account, as the unilateral GHG control measure may shift flights from a more efficient network (e.g., in the EU) to a less efficient one (e.g., in the U.S.).²⁴ However, the change in GHG

²⁴ Note that for the U.S. and the EU moving towards more liberalizing air market, EU airlines may allow operating their hubs in the U.S. Given a stricter regulation on GHG emissions in the EU, EU airlines may operate more flights through their U.S. hubs.

emissions outside the EU due to the EU ETS is usually ignored in the present empirical studies (e.g., CE Delft, 2005; EC, 2006).

[Table 1 here]

For the uniform pricing case, by substituting equations (23) and (24) into (26), the change in total GHG emissions with the unilateral GHG pricing is given below:

$$E^A - E^B = -\frac{\gamma}{\Omega_2}(11e_H + 15e_K)(15e_K + 11e_H + 4e_F) < 0. \quad (29)$$

Equation (29) suggests that the total GHG emissions will decrease if a country unilaterally imposes GHG pricing. As shown in Proposition 4, domestic flights in countries H and F as well as international flights will decrease after imposing unilateral GHG pricing. Thus, the reduction in GHG emissions by (29) is the sum of the emissions reduction from the three routes. As shown in (29), the reduction is increasing in the (per-unit) emissions in the three routes (i.e., e_H , e_F and e_K).

Proposition 6 In the uniform pricing case, when a country moves toward GHG pricing, total GHG emissions will decrease.

7. Concluding Remarks

The main objective of this paper is to investigate the effects of unilateral GHG pricing implemented at a country's airports on the airline market competition and world emissions. We explored both the price discrimination case and the uniform pricing case, in which a country imposes a single charge at both hub and spoke airports. In the price discrimination case, we found that the unilateral GHG pricing may be positive or negative. This is due to the fact that positive charges are imposed to internalize the negative externality, while the country may subsidize airlines, which may confer a strategic advantage to its home airlines. Yet if the home airline's profit is not taken into account or in the uniform pricing case, the airport charges will increase when the country unilaterally implements GHG pricing. In such cases, a strategic advantage is conferred to foreign airlines. It is because the effects of such (positive) GHG charges have a less adverse impact on the foreign airlines than on the home airlines. Furthermore, the increase in airport charges due to the unilateral GHG pricing leads to a reduction in total market output, and the home airlines' market share will decrease. Consumer surplus of the air travel market will decrease. Finally, in the price discrimination case, total GHG emissions may increase after the unilateral GHG pricing is imposed. This may be due to the fact that domestic flights connecting hub and spoke airports may be shifted from a more efficient flight network to a less efficient one.

The paper has also raised a number of other issues and avenues for future research. First, our analysis assumes that the airlines' network structure is fixed. Given the airline industry moves toward more liberalization, airlines will have more flexibility to choose different networks for their flight operations. From a forward-looking perspective, it

might be important to take the response of airlines network choice into account, when we examine the effects of GHG control measures on the airline industry. For example, note that the emission intensity is increasing in flight distance and the number of taking-offs and landings. As a result, given GHG pricing, airlines may be less likely to use HS networks than FC networks, since the HS networks usually involve longer flying distances and more taking-offs and landings, which would incur higher costs due to the GHG pricing. On the other hand, the unilateral GHG control measure may also lead to inefficient airlines network choice: For example, Albers, et al. (2008) argue that airlines may add an intermediate stop outside of the EU on long international flights, so that the EU emissions charge only applies to the final short leg. As a result, the flying distance and the number of taking-offs and landings may increase, thereby increasing world emissions (see, e.g., Morrell and Lu, 2007, for more discussion about the relationship between airlines network choice and environmental costs).

Second, we take the emission technology of aircrafts to be exogenous. In the long run, airlines may control its aircraft emissions by changing, for example, its speed of aircraft replacement, aircraft size and load factor. Thus, it is also practically relevant to take the airlines' decisions which affect emission technology into account, when we examine the effects of GHG control measures. Finally, this paper considers a GHG pricing in a single market – the aviation market. Several empirical studies have been conducted to examine the side effects of the pricing on other industries, for example, tourism (Forsyth, 2008; Forsyth and Ho, 2008), automobile (Hofer, et al., 2008) and

high-speed railways (Benito, 2008). Thus, it is interesting to take other related industries into account in our theoretical analysis.

Finally, this paper only considered GHG emissions, while other externalities due to air transportation, such as congestion, noise and local air pollution, are omitted in the analysis. Note that contemporary estimates (e.g., Quinet and Vickerman, 2004; Schipper, 2004) indicate that the environmental costs of noise and air pollution are at least as large as the costs of GHG emissions. The presence of these other externalities would not be a concern if they were independent of GHG emissions. However, they are likely to be interdependent to a degree. Congestion probably contributes to air pollution and GHG emissions through greater fuel consumption as aircraft fly longer routes, queue on taxiways, and circle airports waiting to land. For similar reasons, congestion contributes to noise. More generally, efforts to reduce one externality are likely to affect the magnitude and spatial distribution of other externalities. It would be interesting to extend this paper to consider the interdependence of GHG emissions and other externalities into account in the analysis.

Figure 1 Network structure

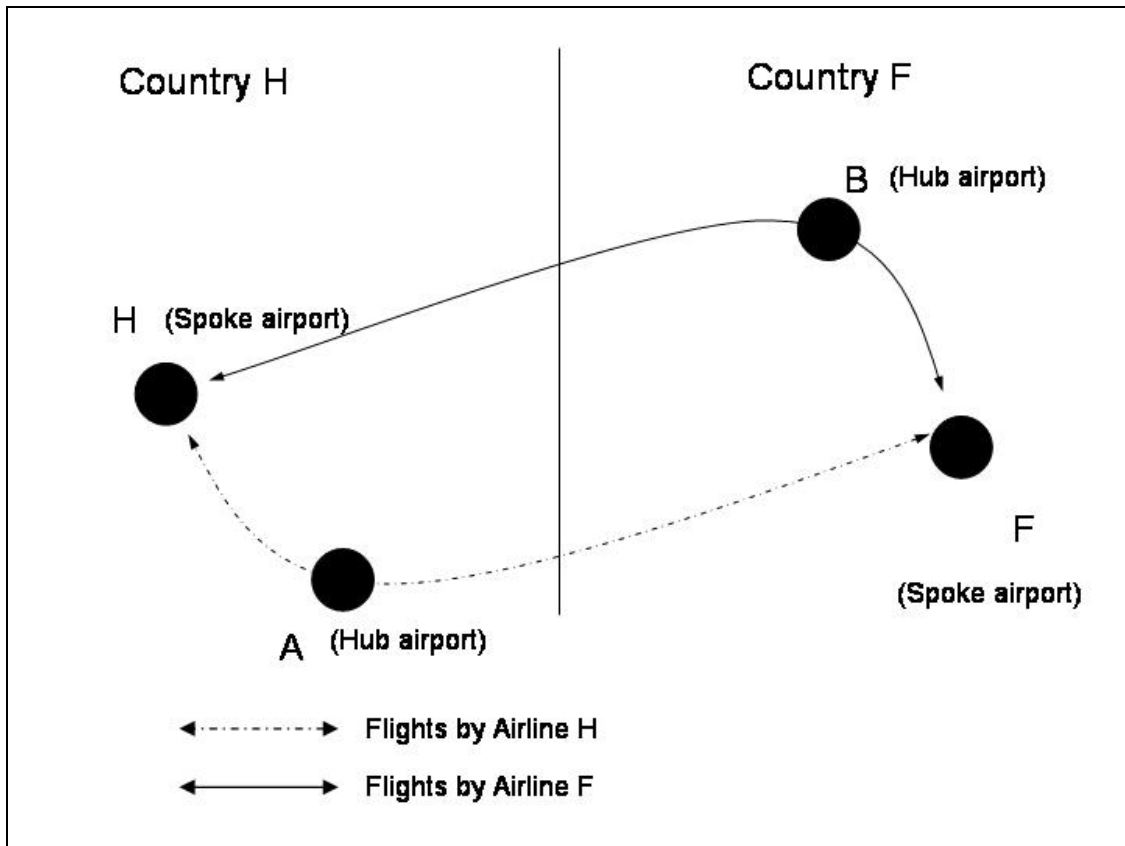


Figure 2 Consumers' distribution and airlines' catchment areas

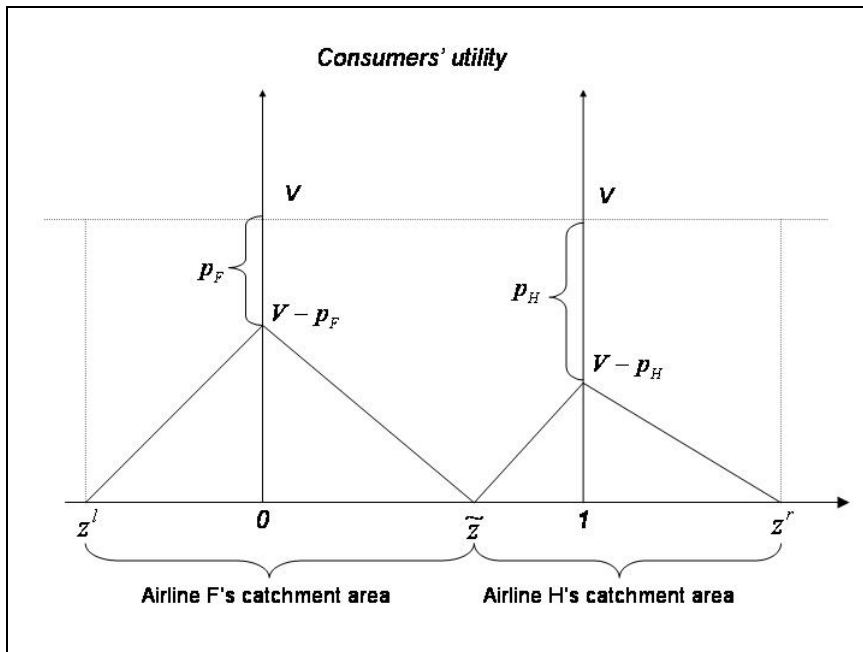


Figure 3 The change in market size and its share after GHG pricing

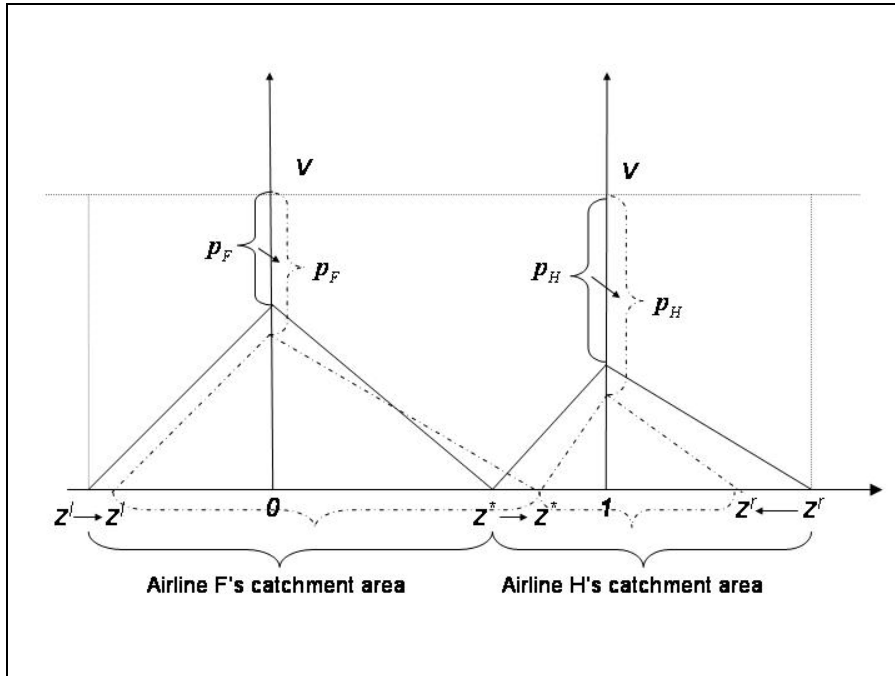


Table 1a CO₂ Emissions of selected routes in US domestic markets^a

From New York to	Per-passenger CO ₂ emission (kg)*	Distance (km)	Emission per distance (kg/km)
Columbus	130.3	774	0.168
Detroit	131.4	816	0.161
Louisville	154.6	1061	0.146
Chicago	157.6	1186	0.133
New Orleans	197.4	1889	0.105
Denver	206.7	2607	0.079
Average	163.0	1389	0.132

Table 1b CO₂ Emissions of selected routes in EU domestic markets

From London to	Per-passenger CO ₂ emission (kg)*	Distance (km)	Emission per distance (kg/km)
Berlin	97.0	946	0.103
Milan	114.2	978	0.117
Barcelona	110.7	1146	0.097
Rome	134.8	1442	0.093
Lisbon	141.7	1564	0.091
Athens	217.6	2242	0.097
Average	136.0	1386	0.099

*Economy class

Source: ICAO Carbon Emissions Calculator

^a. It is shown from the two tables that emission per km decline strongly in the U.S., but not in the EU. Note that the emissions per passenger tend to fall with distance because a significant portion of flight emissions occur during taking-off and landing, and also because larger aircraft are used for long-distance flight which produce fewer emissions per passenger (e.g., Schipper, 2004).

References

- Albers, S., Buhne, J. and Peters, H. (2008) "Will the EU-ETS Instigate Airline Network Reconfigurations?" *Journal of Air Transport Management*, forthcoming.
- Arthur Andersen (2001) Emissions Trading for Aviation, a study commissioned by the International Air Transport Association, London.
- Basso, L.J. and Zhang, A. (2007a) "Congestible Facility Rivalry in Vertical Structures", *Journal of Urban Economics*, 61, 218-237.
- Basso, L.J. and Zhang, A. (2007b) "An Interpretative Survey of Analytical Models of Airport Pricing", in: Lee, D. (Ed.), *Advances in Airline Economics*, Vol.2, Elsevier, 89-124.
- Benito, A. (2008) "Climate Change Impact as a Constraint to the Air Transport Growth: The European Case", Chapter presented at World Conference on Transport Research, Berkeley, California.
- Brander, J.A. (1995) "Strategic Trade Policy", in: Grossman, G. and Rogoff, K. (Eds.), *Handbook of International Economics*, Vol. III, Elsevier Science, Amsterdam.
- Brander, J.A. and Zhang, A. (1990) "Market Conduct in the Airline Industry: An Empirical Investigation", *RAND Journal of Economics*, 21, 567-583.
- Brueckner, J.K. (2004) "Network Structure and Airline Scheduling", *Journal of Industrial Economics*, 52, 291-312.
- Brueckner, J.K. and Flores-Fillol, R. (2007) "Airline Schedule Competition", *Review of Industrial Organization*, 30, 161-177.

- Brueckner, J.K. and Girvin, R. (2008) “Airport Noise Regulation, Airline Service Quality, and Social Welfare”, *Transportation Research Part B*, 42, 19-37.
- Brueckner, J.K. and Zhang, Y. (2001) “A Model of Scheduling in Airline Networks: How a Hub-and-Spoke System Affects Flight Frequency, Fares and Welfare”, *Journal of Transport Economics and Policy*, 35, 195-222.
- Caves, D.W., Christensen, L.R. and Tretheway, M.W. (1984) “Economies of Density versus Economics of Scale: Why Trunk and Local Service Airline Costs Differ”, *RAND Journal of Economics*, 15(4), 471–489.
- CE Delft (2005) Giving Wings to Emission Trading – Inclusion of Aviation under the European Emission Trading System (ETS): Design and Impacts, study commissioned by the European Commission, Delft.
- CE Delft (2007) Allocation of Allowances for Aviation in the EU ETS: The Impact on the Profitability of the Aviation Sector under High Levels of Auctioning. Final report, Delft.
- Chua, C.L., Kew, H. and Yong, J. (2005) “Airlines Code-Share Alliances and Costs: Imposing Concavity on Translog Cost Function Estimation”, *Review of Industrial Organization*, 26(4), 461-487.
- Ciliberto, F. and Williams, J.W. (2007) “Limited Access to Airport Facilities and Market Power in the Airline Industry”, Working paper, Department of Economics, University of Virginia.
- Copeland, B.R. and Taylor, M.S. (1994) “North-South Trade and the Environment”, *Quarterly Journal of Economics*, 109, 755–787.

- Douglas, G.W. and Miller, J.C. (1974) "Quality Competition, Industry Equilibrium, and Efficiency in the Price-constrained Airline Market", *American Economic Review*, 64 (4), 657-669.
- EC (2006) Full Assessment Report, accompanying document to the Proposal for a Directive of the European Parliament and of the Council, European Commission.
- Ederington, J., Levinson, A. and Minier, J. (2005) "Footloose and Pollution-free", *Review of Economics and Statistics*, 87, 92-100.
- Eskeland, G.S. and Harrison, A.E. (2003) "Moving To Greener Pastures? Multinationals and The Pollution Haven Hypothesis", *Journal of Development Economics*, 70, 1-23.
- Forsyth, P. (2008) "Emissions Trading Schemes – Should International Aviation be Excluded?", *manuscript*.
- Forsyth, P. and Ho, T.V. (2008) "Aviation's Indirect Carbon Emissions: Measurement and Implications", Paper for the German Aviation Research Society Workshop Aviation and Climate Change, Amsterdam, July.
- Grossman, G.M. and Krueger, A.B. (1991) "Environmental Impacts of a North American Free Trade Agreement", NBER Working Paper No. 3914, National Bureau of Economic Research, Cambridge, Massachusetts.
- Hansen, M.M., Gillen, D., Djafarian-Tehrani, R. (2001) "Aviation Infrastructure Performance and Airline Cost: A Statistical Cost Estimation Approach", *Transportation Research Part E*, 37, 1-23.
- Hendricks, K., Piccione, M. and Tan, G. (1995) "The Economics of Hubs: The Case of Monopoly", *Review of Economic Studies*, 62, 83-99.

- Hendricks, K., Piccione, M. and Tan, G. (1999) "Equilibria in Networks", *Econometrica*, 67, 1407-1434.
- Hodgkinson, D., Coram, A. and Garner, R. (2007) Strategies for Airlines and Aircraft Emissions and Climate Change: Sustainable, Long-Term Solutions, Hodgkinson Group, Working Paper No 2, June.
- Hoel, M. (1991) "Global Environmental Problems: The Effects of Unilateral Actions Taken by One Country", *Journal of Environmental Economics and Management*, 20, 55-70.
- Hofer, C., Dresner, M. and Windle, R. (2008) "The Environmental Effects of Airline Carbon Emissions Taxation in the U.S.", Paper presented at Air Transport Research Society Conference, Athens.
- IATA (2006) Economics Briefing Impact of the Rise in UK Air Passenger Duty, International Air Transport Association.
- ICAO (2007) Report on Voluntary Emissions Trading for Aviation, Preliminary Edition, International Civil Aviation Organization.
- IPCC (2007) Fourth Assessment Report, Technical Summary, Intergovernmental Panel on Climate Change.
- Kahn, M.E. (2003) "The Geography of US Pollution Intensive Trade: Evidence from 1958 to 1994", *Regional Science and Urban Economics*, 33, 383-400.
- Kumbhakar, S.C. (1990) "A Reexamination of Returns to Scale, Density and Technical Progress in U.S. Airlines", *Southern Economic Journal*, 57, 428-442.

- Kumbhakar, S.C. (1992) "Allocative Distortions, Technical Progress, and Input Demand in U.S. Airlines: 1970–1984", *International Economic Review*, 33, 723-737.
- Levinson, A. and Taylor, M.S. (2004) "Unmasking the Pollution Haven Effect", NBER Working Paper No.10629, National Bureau of Economic Research, Cambridge, Massachusetts.
- Morrell, P. and Lu, C. (2007) "The Environmental Cost Implication of Hub-hub versus Hub By-pass Flight Networks", *Transportation Research Part D*, 12, 143-157.
- Olsthoorn, X. (2001) "Carbon Dioxide Emissions from International Aviation 1905-2050", *Journal of Air Transport Management*, 7, 87-93.
- Oum, T.H., Zhang, A. and Zhang, Y. (1993) "Inter-firm Rivalry and Firm-specific Price Elasticities in Deregulated Airline Markets", *Journal of Transport Economics and Policy*, 27, 171-192.
- Oum, T.H., Zhang, A. and Zhang, Y. (1995) "Airline Network Rivalry", *Canadian Journal of Economics*, 28, 836-857.
- Quinet, E. and Vickerman, R. (2004), *Principles of Transport Economics*, Cheltenham and Northampton, Mass: Edward Elgar.
- Scheelhaase, J.D. and Grimme, W.G. (2007) "Emissions Trading for International Aviation – An Estimation of the Economic Impact on Selected European Airlines", *Journal of Air Transport Management*, 13, 253-263.
- Scheelhaase, J.D., Grimme, W.G. and Schaefer, M. (2008) "The Inclusion of Aviation into the EU Emission Trading Scheme – Impacts on Competition between European and non-European Network Airlines", *manuscript*.

Schipper, Y. (2004) “Environmental Costs in European Aviation”, *Transport Policy*, 11, 141-154.

Small, K.A. and Verhoef, E.T. (2007) *The Economics of Urban Transportation*, Routledge, London.

Stern, N. (2006) *Stern Review Report on the Economics of Climate Change*, a report to the Prime Minister and the Chancellor of the Exchequer on the Economics of Climate Change, United Kingdom.

Ubbels, B., and Verhoef, E.T. (2008) “Governmental Competition in Road Charging”, *Regional Science and Urban Economics*, 38, 174-190.

World Bank (2007) *State and the Trends of Carbon Market 2007*, The World Bank Institute, Washington, D.C.

Xu, X. (2000) “International Trade and Environmental Regulation: Time Series Evidence and Cross Section Test”, *Environmental and Resource Economics*, 17, 233-257.

Yuen, Basso and Zhang, 2008

Zhang, A., Zhang, Y. and Clougherty, J.A. (2008) “Competition and Regulation in Air Transport”, *Handbook of Transport Economics*, Edward Edgar, forthcoming.

Appendix

Derivation of GHG pricing for the price discrimination case

To solve the welfare maximization problem in (13), we first derive consumer surplus CS :

$$CS = \int_0^{|z_l|} [V - p_H(q_H, q_F) - 4\tau z] dz + \int_0^{\tilde{z}} [V - p_H(q_H, q_F) - 4\tau z] dz \\ + \int_0^{1-\tilde{z}} [V - p_F(q_H, q_F) - 4\tau z] dz + \int_0^{z_F} [V - p_F(q_H, q_F) - 4\tau z] dz$$

Using (4), (5) and (6), we can solve the integrals to obtain:

$$CS = \tau(q_F^2 + 6q_F q_H + q_H^2 - 4) / 2 . \quad (\text{A.1})$$

Substitute the inverse demand system (6) into airline H's profit function, we have:

$$\pi_H = (2\tau + V - c)q_H - (t_H^S + t_H^U + t_F^S)q_H - 3\tau q_H^2 - \tau q_H q_F . \quad (\text{A.2})$$

With (A.1) and (A.2), the welfare maximization problem (13) can be written as:

$$SW_H = \alpha[\tau(q_F^2 + 6q_F q_H + q_H^2 - 4) / 2] + \beta[(2\tau + V - c)q_H \\ - t_F^S q_H - 3\tau q_H^2 - \tau q_H q_F + t_H^S q_F - \alpha[e_H q_H + \delta e_K (q_H + q_F)]] \quad (\text{A.3})$$

The first-order conditions for the maximization problem with respect to t_H^S and t_H^U are,

$$\frac{dSW_H}{dt_H^S} = \frac{\partial SW_H}{\partial q_H} \frac{\partial q_H}{\partial t_H^S} + \frac{\partial SW_H}{\partial q_F} \frac{\partial q_F}{\partial t_H^S} + \frac{\partial SW_H}{\partial t_H^S} = 0 , \quad (\text{A.4})$$

$$\frac{dSW_H}{dt_H^U} = \frac{\partial SW_H}{\partial q_H} \frac{\partial q_H}{\partial t_H^U} + \frac{\partial SW_H}{\partial q_F} \frac{\partial q_F}{\partial t_H^U} + \frac{\partial SW_H}{\partial t_H^U} = 0. \quad (\text{A.5})$$

and assuming the second-order conditions are satisfied.

By solving conditions (A.4) and (A.5),

$$t_H^U = \left\{ \frac{5[14 - \beta + \tau(\beta - 4\alpha)]}{\Omega_1} e_H + \frac{30(2 - \tau)\beta\delta}{\Omega_1} e_K \right\} \gamma + K_1,$$

$$t_H^S = \left\{ \frac{6\beta + 17\alpha\tau - 6\beta\tau}{\Omega_1} e_H + \frac{[70 - 65\beta + (29\beta + 14\alpha)\tau]\delta}{\Omega_1} e_K \right\} \gamma + K_2.$$

where $\Omega_1 = -(\tau - 1)^2 \beta^2 + 2(34\tau + 3\alpha\tau - 70)\beta - 4(2\alpha\tau + 3)\alpha\tau + 140 > 0$ by the second-order conditions; and

$$K_1 = \frac{1}{\Omega_1} \{ [(\tau - 1)^2 \beta^2 + [69 - 3\tau(2\alpha + 11)]\beta + \alpha\tau(8\alpha\tau + 9) - 70] t_F^U$$

$$+ [(\tau - 1)^2 \beta^2 - [75 + 3\tau(2\alpha - 13)]\beta + \alpha\tau(8\alpha\tau + 26) - 70] t_F^S$$

$$- [2\tau^3 + (V - c - 4)\tau^2 + 2(c - V + 1)\tau + V - c] \beta^2$$

$$- [-2(6\alpha + 39)\tau^2 + 3[(2\alpha + 13)(c - V) + 50]\tau + 75(V - c)] \beta$$

$$- 16\alpha^2 \tau^3 - 4\alpha\tau^2 [13 + 2\alpha(V - c)] + (70 - 26\alpha\tau)(V - c) + 140\tau \}$$

$$K_2 = \frac{1}{\Omega_1} \{ -[(\tau - 1)^2 \beta^2 - [75 - 3\tau(2\alpha + 11)]\beta + 8\alpha\tau(\alpha\tau - 1) - 70] t_F^U - 30\beta(\tau - 2) t_F^S$$

$$- 30\beta[2(V - c) - (4 - V + c)\tau + 2\tau^2] \}$$

Derivation of GHG pricing for the uniform pricing case

The first-order condition for the maximization problem with respect to \bar{t}_H is,

$$\frac{dSW_H}{dt_H} = \frac{\partial SW_H}{\partial q_H} \frac{\partial q_H}{\partial t_H} + \frac{\partial SW_H}{\partial q_F} \frac{\partial q_F}{\partial t_H} + \frac{\partial SW_H}{\partial t_H} = 0, \quad (\text{A.6})$$

and assuming the second-order condition is satisfied.

By solving conditions (A.6),

$$\bar{t}_H = \frac{35}{\Omega_2} (11e_H + 15\delta e_K)\gamma + K_5,$$

where $\Omega_2 = -401\alpha\tau + 814\beta\tau - 1540\beta + 1820 > 0$ by the second-order condition; and

$$K_5 = \frac{1}{\Omega_2} \{ [(655 - 401\tau)\beta + 499\alpha\tau - 655]\bar{t}_F + [(810\tau - 1470)\tau + (405\tau - 735)(V - c)]\beta - 25[24\alpha\tau^2 + 6[2\alpha(V - c) - 7]\tau - 21(V - c)] \}$$