Effects of the use-it-or-lose-it rule on airline strategy and climate

by

Till Kösters, Marlena Meier and Gernot Sieg

Institute of Transport Economics Münster
Working Paper
No. 36
January 2023

wissen.leben
WWU Münster

© Westfälische Wilhelms-Universität (WWU),
Institute of Transport Economics, 2022

Address
Institut für Verkehrswissenschaft
Am Stadtgraben 9
D 48143 Münster, Germany

Telephone
+49 251 83-22 99 4

Fax
+49 251 83-28 39 5

E-Mail
verkehrswissenschaft@uni-muenster.de

Website
http://www.iv-muenster.de

All rights reserved.

Any reproduction, publication and reprint in the form of a different publication, whether printed or produced electronically, in whole or in part, is permitted only with the explicit written authorisation of the Westfälische Wilhelms-Universität, Institute of Transport Economics, or the author(s).

The views expressed in this paper do not necessarily reflect those of the Institute of Transport Economics or the WWU.

The Working Paper Series seeks to disseminate economic research work by the WWU, Institute of Transport Economics staff and visitors. Papers by researchers not affiliated with the WWU Institute of Transport Economics may also be considered for publication to the extent that they have been presented at research seminars/workshops organised by the institute.

The working papers published in the Series constitute work in progress circulated to stimulate discussion and critical comments. Views expressed represent exclusively the authors' own opinions.

The Series is managed by the Director of the Institute of Transport Economics.

Effects of the use-it-or-lose-it rule on airline strategy and climate

By Till Kösters*,† Marlena Meier* and Gernot Sieg*

Grandfather rights require airlines to operate at least 80 % of their slots, if they are to keep them in the next scheduling period. To prevent losing slots, the airlines may operate slot-rescue flights, an airline strategy called slot hoarding. We model strategies of a monopolistic airline which chooses between long-haul and short-haul flights at a slot-coordinated airport. In cases of a binding use-it-or-lose-it rule, we observe a bias in the airline route network in favor of slot-rescue flights on short-haul distances. Slot-rescue flights reduce airline profits, but raise consumer surplus and airport profits. The overall effect of slot-rescue flights on welfare, however, remains ambiguous. Recently, slot hoarding and its climate impact have received considerable attention during the COVID-19 pandemic. We show that the environmental effects of slot-rescue flights are asymmetric. The climate damage of slot hoarding in the EU is reduced by the EU ETS, whereas CORSIA is rather ineffective.

Keywords: Use-it-or-lose-it rule, Slot hoarding, Climate damage, EU ETS, CORSIA, COVID-19
JEL: L93, R48, Q51

I. Introduction

Slot control mechanisms are intended to limit the number of take-off and landing operations at busy airports worldwide, in order to avoid congestion and delay. Slots are not attached to a route, and thus airlines are free to adjust their networks to demand developments (European Parliament et al., 2016). Airlines that are entitled to use slots at congested airports gain market power. Since slots are a valuable asset for airlines, slot allocation is often regulated (Button, 2020; Czerny, 2020).

The slot allocation process at slot-coordinated airports usually follows the Worldwide Airport Slot Guidelines (WASG) (ACI et al., 2020) and takes place bi-annually. Basically, slot allocation relies on historic rights, so-called *grandfather rights*, and requires airlines to use slots at least to 80 % (80/20), in order to retain their slots in the next scheduling period (the *use-it-or-lose-it* rule). Otherwise, the slots will be reallocated to potential entrants and competitors. In Europe, the slot allocation process is strictly regulated by Council Regulation (EEC) No. 93/95 of 1993.[1] The regulation refers to the entire airport infrastructure required to operate a flight on a specific date and time, mandatory for more than 100

---

* University of Münster, Institute of Transport Economics, Am Stadtgraben 9, 48143 Münster, Germany
† Corresponding author: E-Mail: till.koesters@uni-muenster.de

The final publication in “Transportation Research Part D” is available online at: http://doi.org/10.1016/j.trd.2022.103570.

[1] The regulation applies not to a single take-off and landing right, but to a series of slots. A slot series consists of at least five slots at the same time on the same weekday within a flight schedule period. Most of the literature uses the terms *slots* and *slot series* synonymously.

slot-coordinated airports. Unlike in Europe, the slot regulation in the United States applies only to the use of runways. Only a few airports in the United States are runway slot-coordinated, e.g. JFK and LGA. All other airports are subject to formal schedule review or have unrestricted access to runways on a *first-come-first-serve* basis (FAA, 2022).

Furthermore, the declared airport capacity in the United States is scheduled according to Visual Meteorological Conditions, i.e. at good weather-conditions capacity, whereas European airport capacity is declared according to Instrument Meteorological Conditions, i.e. bad weather conditions (Gillen et al., 2016). Gillen et al. (2016) demonstrate the trade-off between declared airport capacity and punctuality. Demand management in the United States facilitates access to airport infrastructure, but delays increase during the day. In Europe, both the slot allocation system and the comparatively lower declared airport capacity, lead to rather moderate and constant delays, but on the other hand, can also result in an underuse of available airport capacity (Morisset and Odoni, 2011; European Parliament et al., 2016; Gillen et al., 2016). Madas and Zografos (2008) point out that inefficiencies in the use of available airport capacity rely on a supply shortage of slots, while simultaneously, up to 20 % of allocated slots are unused. The authors attribute this to a mismatch between slots at the origin and destination airports. Furthermore, the slot allocation process, such as at European airports, has been criticized for reducing airline competition, as particularly incumbent airlines benefit from grandfather rights (Forsyth, 2007; European Parliament et al., 2016; Gillen et al., 2016). Moreover, the slot allocation system may lead to anti-competitive behavior on the part of incumbent airlines. In order to satisfy the 80 %-rule, incumbent airlines operate excessive flights to retain their allocated slots in the next scheduling period. Incumbent airlines tend to perform these so-called *slot-rescue flights* with smaller aircraft and lower load factors, rather than to lose their slots (de Wit and Burghouwt, 2008; Fu et al., 2015; European Parliament et al., 2016). Thereby, incumbent airlines keep slot mobility low and deter market entry for potential entrants. Such behavior is called *slot hoarding*, and received some publicity in 2022 from German airline Lufthansa AG CEO Carsten Spohr claiming: "We have to operate 18,000 additional, unnecessary flights during the winter, purely to secure our slots."[2] Additional flights emit additional greenhouse gases which may accelerate climate change. However, the extent of climate damage from slot-rescue flights depends on origin and destination airport, in combination with the regulation of greenhouse gas emissions valid for these flights.

A. *Related literature*

So far, slot hoarding has attracted relatively little interest in the literature.[3] In Europe, slot-hoarding behavior is difficult to assess, since all major airports are slot-coordinated, and thus cannot be compared with major non slot-coordinated airports, whereas in the United States, a comparison with major non-slot-coordinated airports is possible (European Parliament et al., 2016). Fukui (2012) found a negative impact of slot allocation on aircraft size. The more slots an airline

---

[2] "Aber wir müssen im Winter 18.000 zusätzliche, unnötige Flüge durchführen, nur um unsere Start-und Lande-Rechte zu sichern."(Frankfurter Allgemeine Zeitung, 2021)

[3] Kleit and Kobayashi (1996), Forsyth (2007), de Wit and Burghouwt (2008), Sieg (2010), Fukui (2012), United States Government Accountability Office (2012), Fu et al. (2015), European Parliament et al. (2016), Miranda and Oliveira (2018) and Sheng et al. (2019).

holds, the smaller the aircraft size and the higher the incentive to keep slots out of the hands of competitors. Furthermore, a study from the United States Government Accountability Office (2012) observes a higher frequency, smaller aircraft and lower load factors at slot-coordinated airports, which may be indicators of slot-hoarding behavior.

In a theoretical framework, Sieg (2010) investigates how both a monopolistic airline and an airport respond strategically to the grandfather policy. According to the results, the airport benefits from grandfather policy, since negative effects are transferred to airlines, resulting in higher airport profits, lower airline profits and lower social welfare. Sheng et al. (2019) extend the theoretical framework of Sieg (2010) by introducing flight frequency and aircraft size in order to specify slot-hoarding behavior. As a consequence of grandfather policy, airlines operate excessive flights with smaller aircraft and carry more passengers. Conclusively, the few studies on this issue underline that current slot-allocation regulation leads to airline network decision distortion on the optimal use of slots.

The aviation sector emits various greenhouse gases and is therefore a contributor to climate change (Ryley et al., 2020; IPCC, 1999). Emissions in the aviation sector are addressed by the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), and the EU Emission Trading System (EU ETS). CORSIA is an offset scheme, whereas the EU ETS is a cap-and-trade system. The inclusion of the aviation sector in the EU ETS in 2012 has been analyzed ex-ante concerning its competitive, environmental and macroeconomic impacts (Anger, 2010; Scheelhaase et al., 2010; Malina et al., 2012). Scheelhaase et al. (2018) compare the EU ETS and CORSIA from an environmental and competitive perspective. Maertens et al. (2019) and ICF Consulting et al. (2020) evaluate the environmental effectiveness of both schemes in order to give proposals for an effective co-existence of the EU ETS and CORSIA. They conclude that the EU ETS is more ambitious, since the emission cap aims at higher emission reduction than CORSIA, which only offsets additional emissions compared to the high and rigid baseline level. Moreover, the authors raise concerns about the effectiveness of CORSIA emission offsetting projects. Hence, they recommend a preservation of the EU ETS for flights within the European Economic Area (EEA), a view supported by Scheelhaase et al. (2021). Scheelhaase and Maertens (2020) provide suggestions for improving CORSIA's environmental efficiency, e.g. including flights of large domestic aviation markets such as the United States or China. According to Efthymiou and Papatheodorou (2019), the environmental efficiency of the EU ETS can be improved, for instance by reducing the amount of free allocated allowances.

B. *Contribution*

Whether or not a slot-rescue flight damages the climate depends, as this paper shows, on the nature of regulation. We extend the model of Sheng et al. (2019) by enabling airlines to choose between short-haul and long-haul flights, i.e. by aligning not only the frequency of flights and aircraft size, but also the route network. When the use-it-or-lose-it rule is binding, a profit-maximizing monopolistic airline would then operate slot-rescue flights in particularly with smaller aircraft in the short-haul market. Slot-rescue flights can both increase or reduce welfare, depending on the use-it-fraction, and the ratio of declared airport capacity to optimal flight frequency without grandfather policy. Passengers benefit from an increased frequency, whereas the hub airport receives higher revenue from additional passenger volume. However, slot-rescue flights reduce airline profits, as the frequencies under grandfather policy exceed the frequencies when there is no concern about slot losses.

This paper also contributes to the growing literature on aviation decarbonization. We demonstrate the asymmetric environmental effects of slot-rescue flights through EU ETS and CORSIA. At European airports, airlines usually hoard slots by operating short-haul flights within the EEA. Emissions from such slot-rescue flights are covered by the EU ETS and thus abated elsewhere, either in the aviation sector or at stationary installations. Therefore, climate damage caused by slot hoarding at European Airports is almost entirely prevented by the EU ETS. On the other hand, CORSIA only accounts for international flights between ICAO member states. To make matters worse, those flights' emissions will only be offset if they are additional to the baseline level. In large countries, such as the United States or China, the majority of flights, especially slot-rescue ones, are domestic and therefore not subject to CORSIA. Both characteristics of slot-rescue flights, no additionality to the baseline level and mostly domestic, result in CORSIA being rather ineffective in preventing negative environmental effects of slot hoarding.

The remainder of this paper is structured as follows. In Section II, the theoretical framework is defined, and an airline route network analysis conducted for both a market environment with a non-capacity-constraint airport as well as a slot-coordinated airport. Furthermore, we analyze the welfare effects of the grandfather policy. Section III provides an overview of adjustments of the grandfather policy during the COVID-19 pandemic. In Section IV, we explain the scope of the EU ETS and CORSIA and discuss whether emissions from slot-rescue flights are covered by them. Section V concludes.

II. Theoretical model

We model a monopolistic airline strategy of choosing long-haul and short-haul flights at both a non-capacity constraint and a slot-coordinated airport. For this purpose, we extend the model of Sheng et al. (2019).

A. *Basic monopoly airline model*

We consider a hub-and-spoke (HS) network (see Figure 1) similar, for example, to Oum et al. (1995), Brueckner (2004), and Álvarez-Sanjaime et al. (2020). We do not explicitly consider connecting passengers. We assume that there is only one airline with monopolistic market power. This airline is located at the hub airport H and connects the spoke airports A and B with either a domestic short-haul flight or an international long-haul flight.

We assume ticket demand q_A for the route HA and q_B for the route HB. p_i is the airfare imposed by the airline for the two different routes $i \in \{A, B\}$, ω_i illustrates basic willingness to pay for the respective route. b_i denotes the price sensitivity, i.e. the slope of the inverse demand function. We incorporate that a higher flight frequency reduces passengers' schedule delay costs such that departing and arrival times closely match passenger preferences, thereby increasing willingness to pay. Brueckner (2004) models a concave specification of schedule delay costs and flight frequency. We follow Heimer and Shy (2006), Flores-Fillol (2009), D'Alfonso et al. (2016), and Sheng et al. (2019) and assume positive and

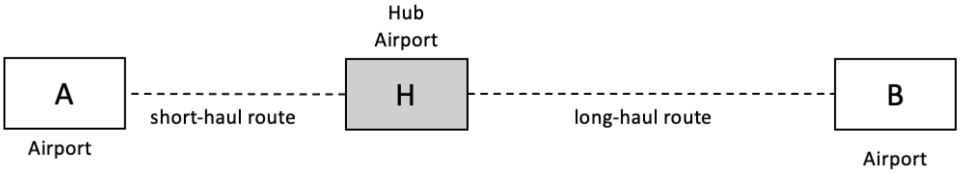

Figure 1. : Hub-and-spoke model

Three airports, two spoke airports (A and B) and the hub airport (H) entail two routes, one short-haul and one long-haul operated by one monopolistic airline.

constant marginal benefits γ of flight frequency f_i, i.e. the number of flights per time period. Although a concave specification more accurately describes the impact of a higher flight frequency on schedule delay costs, the conclusions derived from the model are not limited by the linear specification. To summarize, the system of indirect demand is

$$p_i = \omega_i + \gamma f_i - bq_i, \quad i \in \{A, B\}.$$

We distinguish between airport-related costs and network coordination costs (Brueckner, 2004; Sheng et al., 2019; Álvarez-Sanjaime et al., 2020). For simplicity, only hub airport H imposes a per passenger airport fee τ, identical for passengers in both short-haul and long-haul markets. Network coordination costs are implemented as a quadratic cost function of flight frequency $k_i f_i^2$ (Heimer and Shy, 2006; Brueckner, 2009; Flores-Fillol, 2009; Álvarez-Sanjaime et al., 2020). A larger airline network is associated with a greater effort to schedule flights. Furthermore, we do not explicitly consider hub passengers, but passengers may transit at the hub airport and benefit from in-time connecting flights and a dense airline network. The organization of such a network is costly, and costs increase with network complexity, which is approximated by flight frequency. The cost parameter k_i depends on flight time, crossing different airspaces, and turnaround times at airports (e.g. Pels, 2008), which is higher for international long-haul flights. Airline total costs of each market can be written as:

$$C_i(q_i, f_i) = \tau q_i + k_i f_i^2, \quad k_i > 0.$$

B. *Nash equilibria in frequency and passenger volume*

NON-CAPACITY-CONSTRAINED AIRPORT

In the absence of both airport slot capacity restrictions and grandfather policy, the airline simultaneously chooses optimal flight frequency and passenger volume to maximize its profit

$$\begin{aligned}\pi &= p_A q_A + p_B q_B - C_A - C_B \\ &= (\omega_A + \gamma f_A - bq_A - \tau)q_A + (\omega_B + \gamma f_B - bq_B - \tau)q_B - k_A f_A^2 - k_B f_B^2.\end{aligned}$$

The FOCs are

$$\frac{\partial \pi}{\partial f_i} = 0 \Rightarrow f_i = \frac{\gamma q_i}{2k_i},$$

$$\frac{\partial \pi}{\partial q_i} = 0 \Rightarrow q_i = \frac{\omega_i + \gamma f_i - \tau}{2b}.$$

By solving the system of FOCs, we obtain the equilibria in frequency and passenger volume for both markets:

$$f_i^* = \frac{\gamma(\omega_i - \tau)}{4bk_i - \gamma^2}, \quad q_i^* = \frac{2k_i(\omega_i - \tau)}{4bk_i - \gamma^2} = \frac{2k_i}{\gamma} f_i^*. \tag{1}$$

Seat capacity, i.e. aircraft size, is defined by $s_i = q_i/(l_i f_i)$, where l_i describes the load factor. According to Brueckner (2004), another approach would be to keep the load factor endogenous and seat capacity exogenous. As we focus in our model on the characteristics of airline route network regarding frequency and seat capacity, we assume the load factor to be exogenous and for simplicity, to be equal to 1 (Brueckner, 2004). Thus, optimal seat capacity is $s_i^* = q_i^*/f_i^* = 2k_i/\gamma$. Airfares are computed by

$$p_i^* = \omega_i + \gamma f_i^* - bq_i^* = \frac{2bk_i(\omega_i + \tau) - \gamma^2 \tau}{4bk_i - \gamma^2}. \tag{2}$$

Both frequency and passenger volume (Eq. (1)) depend positively on basic willingness to pay ω_i and the marginal network benefit γ. The latter reduces schedule delay costs, and therefore increases passenger demand q_i. As a consequence, flight frequency f_i increases in order to serve induced demand. Optimal aircraft size is defined by two countervailing effects. If network coordination costs increase, the airline reduces frequency and uses larger aircraft to take advantage of economies of scale. Moreover, k_i is weighted by factor 2, and therefore amplified. However, if the marginal network benefit γ increases, the airline uses smaller aircraft and increases frequency, thereby reducing schedule delay costs and increasing willingness to pay as well as passenger demand. The airline passes on both network coordination costs k_i and per passenger airport fee τ to passengers through the airfare (Eq. (2)).

The denominator $\xi_i = 4bk_i - \gamma^2$ reveals that frequency is only limited if the marginal benefits γ from frequency are small. When γ^2 approaches $4bk_i$, frequency becomes unbounded. To ensure that the airline operates with bounded frequency, we assume that network coordination cost parameters k_A and k_B are larger than $\gamma^2/4b$. Furthermore, airlines only operate if net willingness to pay is non-negative, i.e. $\omega_i - \tau > 0$.

In general, willingness to pay and costs could be unrelated to the length of a route or the airspaces a route crosses. Usually, willingness to pay is higher for the long-haul route HB than for the short-haul route HA, i.e. $\omega_B > \omega_A > 0$. In addition, flights need to be coordinated at both the departure and the destination airport. This coordination process is more complex for long-haul flights and therefore $k_B > k_A$. If otherwise, coordination for short-haul flights is then more expensive. However, higher network coordination costs of long-haul flights occurs with a longer flight time, crossing different airspaces and a higher probability of delay. Thus, we do not further take into account the fact that $k_A > k_B$.

Figure 2 displays market outcomes of a fictional market, depending on the ratio of network coordination costs. Areas I-III are defined by conditions 3 and 4 and it holds that $k_A < k_B$. Thus, aircraft are smaller in the short-haul market, i.e. $s_A < s_B$. The larger basic willingness to pay ω_A, all else being equal, the

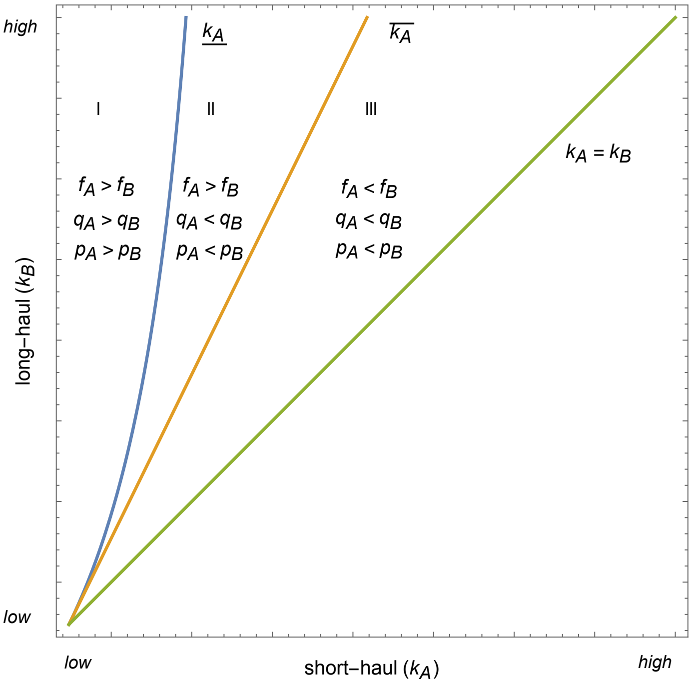

Figure 2. : Network coordination costs

Parameter values are: $\omega_A = 300, \omega_B = 600, \gamma = 10, \tau = 10, b = 0.101$.

larger Areas I and II, and the smaller Area III.

PROPOSITION 1: *Iff*

$$k_A < \frac{4bk_B(\omega_A - \tau) + \gamma^2(\omega_B - \omega_A)}{4b(\omega_B - \tau)} = \overline{k_A}, \tag{3}$$

then $f_A^* > f_B^*$*, i.e. the short-haul market is frequented more (see Appendix .A).*

PROPOSITION 2: *Iff*

$$k_A > \frac{\gamma^2 k_B(\omega_B - \tau)}{4bk_B(\omega_B - \omega_A) + \gamma^2(\omega_A - \tau)} = \underline{k_A} \tag{4}$$

then $q_A^* < q_B^*$ *and* $p_A^* < p_B^*$*, i.e. the airline carries more passengers and charges a higher airfare on the long-haul route (see Appendix .B).*

In Areas I and II, condition 3 is satisfied. Here, the airline operates more short-haul flights ($f_A > f_B$), since network coordination costs on route HA are comparatively low. A denser airline network reduces passengers' schedule delay costs, and thus enhances willingness to pay and induces additional demand. Since $f_A > f_B$, the network benefit in the short-haul market is greater than in the long-haul market. If $k_A < \underline{k_A}$, both the airfares and the passenger volume are higher in the short-haul market. If k_A equals $\underline{k_A}$, airfares and the passenger volume are the same in both markets. When conditions 3 and 4 are satisfied ($\underline{k_A} < k_A < \overline{k_A}$), the short-haul market is still more frequented than the long-haul market, but the network effect of the short-haul market is lower compared to Area I. This results in lower airfares and passenger volume in the short-haul market. Area II depicts the most representative and intuitive situation.

Slot-coordinated airport

There are various studies that analyze airline network choice under slot consideration, but without taking into account compliance with the use-it-or-lose-it rule (see e.g. Barbot, 2004; Adler, 2005; Adler et al., 2014). We now consider a monopolistic airline at a slot-coordinated hub airport H. Declared airport capacity at H, defined in slots, is $\overline{M}$. All available slots $\overline{M}$ are allocated to the monopolistic airline. The total number of flights is described by $\sum f_i$ and it holds that $\sum f_i \leq \overline{M}$. $\theta \in (0; 1]$ defines the use-it-or-lose-it rule (Sheng et al., 2019). At a grandfathered airport, the airline has an incentive to keep its slots in the next scheduling period if the discounted net profit of holding a slot exceeds the marginal loss of operating a flight to rescue the slot. Slots are scarce and therefore valuable. Furthermore, if underutilization is caused by a sudden demand shock, slots could be useful and profitable, once passenger demand increases in the future. The slot-rescue flight secures this rent for the airline. We assume that this is the case and that the airline is unwilling to give up these rents. Conclusively, the airline ensures the minimum slot usage needed to abide by the use-it-or-lose-it rule ($\sum f_i \geq \theta\overline{M}$) in order to keep their slots in the next scheduling period. As slot-hoarding behavior occurs only at a slot-coordinated airport subject to grandfather policy, we do not discuss alternative slot-allocation mechanisms such as airport slot trading and slot auctions (see e.g. Fukui, 2010, 2014; Sheng et al., 2015).

In accordance with Sheng et al. (2019), the airline maximizes its profit

$$\max \pi^{GF} = p_A q_A + p_B q_B - C_A - C_B \tag{5}$$

subject to the use-it-or-lose-it rule

$$\theta\overline{M} \leq \sum f_i. \tag{6}$$

The Lagrangian function is defined by

$$\begin{aligned}\mathcal{L}(f_A, f_B, q_A, q_B, \lambda) =& (\omega_A + \gamma f_A - b q_A - \tau) q_A + (\omega_B + \gamma f_B - b q_B - \tau) q_B \\ & - k_A f_A^2 - k_B f_B^2 - \lambda(\theta\overline{M} - f_A - f_B).\end{aligned}$$

The corresponding Lagrangian conditions are as follows

$$\begin{aligned}\tfrac{\partial\mathcal{L}}{\partial f_i} &= \gamma q_i - 2 f_i k_i + \lambda = 0 \Rightarrow f_i = \tfrac{\gamma q_i + \lambda}{2k_i}, \\ \tfrac{\partial\mathcal{L}}{\partial q_i} &= \omega_i + \gamma f_i - 2b q_i - \tau = 0 \Rightarrow q_i = \tfrac{\omega_i + \gamma f_i - \tau}{2b}, \\ \tfrac{\partial\mathcal{L}}{\partial\lambda} &= f_i + f_j - \theta\overline{M} = 0 \Rightarrow \theta\overline{M} = f_i + f_j.\end{aligned}$$

By solving the system of FOCs, we obtain solutions subject to the grandfather policy for both markets:

$$\begin{aligned} f_i^{GF} &= \frac{\theta\overline{M}(4bk_j - \gamma^2) + \gamma(\omega_i - \omega_j)}{2(2b(k_i + k_j) - \gamma^2)} \\ &= \theta\overline{M}\frac{\xi_j}{\xi_i + \xi_j} + \frac{\gamma(\omega_i - \omega_j)}{\xi_i + \xi_j}, \end{aligned} \tag{7}$$

$$\begin{aligned} q_i^{GF} &= \frac{\gamma\theta\overline{M}(4bk_j - \gamma^2) + (\omega_i - \tau)4b(k_i + k_j) - \gamma^2(\omega_i + \omega_j - 2\tau)}{4b(2b(k_i + k_j) - \gamma^2)} \\ &= \frac{1}{2b}\left[\gamma\theta\overline{M}\frac{\xi_j}{\xi_i + \xi_j} + \omega_i\frac{\xi_i}{\xi_i + \xi_j} - \tau + \frac{\omega_i 4bk_j - \omega_j\gamma^2}{\xi_i + \xi_j}\right]. \end{aligned} \tag{8}$$

Market outcomes in Eq. (7) and (8) describe the interdependencies of both markets due to airport capacity restrictions. In Eq. (7), the first term illustrates how the airline distributes its flight frequencies across both markets to satisfy the required minimum slot usage $\theta\overline{M}$. Since $k_A < k_B$, and thereby $\xi_A < \xi_B$, the slot distribution factor $\xi_j/(\xi_i + \xi_j)$ is higher for the short-haul market. Thus, the airline operates more flights in the short-haul market. The second term, however, depends on the difference in willingness to pay $\omega_i - \omega_j$. Since we assume that $\omega_A < \omega_B$, flight frequency decreases in the short-haul market and increases in the long-haul market by the same ratio. Similar to flight frequency, passenger demand (Eq. (8)) also depends on the required minimum slot usage. In addition, the product of willingness to pay and the slot distribution factor affects passenger demand positively and decreases with the per passenger airport fee. The last term demonstrates that higher network coordination costs in one market have a positive impact on passenger demand in the other market. The preceding factor $1/2b$ describes a negative correlation between price sensitivity and passenger demand.

Equilibrium airfares are then calculated to

$$p_i^{GF} = \frac{1}{2}(\omega_i + \tau) + \frac{\gamma\theta\overline{M}(4bk_j - \gamma^2) + \gamma^2(\omega_i - \omega_j)}{4(2b(k_i + k_j) - \gamma^2)} = \frac{1}{2}\left[\omega_i + \tau + \gamma f_i^{GF}\right].$$

A denser airline network increases overall willingness to pay, and consequently also airfares. The per passenger airport fee is passed on to passengers. Seat capacity is $s_i = q_i/f_i$, which equals in the equlibrium

$$\begin{aligned} s_i^{GF} &= \frac{\gamma\theta\overline{M}(4bk_j - \gamma^2) + (\omega_i - \tau)4b(k_i + k_j) - \gamma^2(\omega_i + \omega_j - 2\tau)}{2b(\theta\overline{M}(4bk_j - \gamma^2) + \gamma(\omega_i - \omega_j))} \\ &= \frac{1}{2b}\left[\frac{\gamma\theta\overline{M}\xi_j + \xi_i(\omega_i - \tau) - \tau\xi_j + \omega_i 4bk_j - \omega_j\gamma^2}{\theta\overline{M}\xi_j + \gamma(\omega_i - \omega_j)}\right]. \end{aligned}$$

We now analyze an airline's route network decision for a given declared airport capacity. If declared airport capacity $\overline{M} \leq (1/\theta)[(\gamma(\omega_B - \omega_A))/\xi_B]$, then, because of non-profitability, the short-haul market is not served. Since willingness to pay for long-haul flights is higher, slots are exclusively distributed to route HB. A minimum airport capacity of $\overline{M} > (1/\theta)[(\gamma(\omega_B - \omega_A))/\xi_B]$ is required to serve both the long-haul HB and the short-haul route HA.

PROPOSITION 3: *Iff*

$$\overline{M} > \frac{1}{\theta}\left[\frac{\gamma}{2b}\frac{\omega_B - \omega_A}{k_B - k_A}\right], \tag{9}$$

then $f_A^{GF} > f_B^{GF}$*, i.e. the short-haul market is frequented more under a grandfather policy. Iff*

$$\overline{M} < \frac{1}{\theta}\left[\frac{(\omega_B - \omega_A)(k_A + k_B)}{\gamma(k_B - k_A)}\right], \tag{10}$$

then $q_A^{GF} < q_B^{GF}$ *and* $p_A^{GF} < p_B^{GF}$*, i.e. on the long-haul route* HB*, more passengers are carried and a higher airfare is charged (Proof: see Appendix .C).*

If declared airport capacity, and hence required minimum slot usage, is sufficiently large, the flight frequency in the short-haul market exceeds that in the long-haul market, since the slot distribution factor in Eq. (7) allocates more slots to the short-haul market. If declared airport capacity lies within the range defined by conditions 9 and 10, the airline employs smaller aircraft on the short-haul route, i.e. $s_A^{GF} < s_B^{GF}$. Here, the airline carries more passengers and charges higher airfares in the long-haul market. A grandfather policy can distort the airline's route network decision.

C. *Welfare effects of a grandfather policy*

We first analyze the welfare effects of a grandfather policy that results from the distortion of an airline's route network decision. Therefore, we consider a non-capacity-constrained and non-grandfathered airport, where the monopolistic airline offers flights to maximize profits at a frequency of f_i^*. Let $f_A^* + f_B^* = f^*$ and at less than airport capacity $\overline{M}$. Define $\tilde{\theta} = f^*/\overline{M}$ as the highest use-it-or-lose-it threshold that is non-binding for the airline, i.e. the highest threshold with no need for slot-rescue flights. For all $\theta > \tilde{\theta}$, airlines hoard slots by maximizing profits (Eq. (5)) subject to the use-it-or-lose-it rule (Eq. (6)).

PROPOSITION 4: *Iff* $\theta > \tilde{\theta}$*, the use-it-or-lose-it rule induces the airline to operate more flights in both the short-haul market and the long-haul market than in the absence of a grandfather policy (*$f_i^* < f_i^{GF}$*). In particular, the airline operates slot-rescue flights in the short-haul market (*$f_A^{GF} - f_A^* > f_B^{GF} - f_B^*$*).*

In this case, slot-rescue flights are operated in both the short-haul and long-haul markets, but not in the same proportion. The slot distribution factor in Eq. (7) shifts more slot-rescue flights to the short-haul market. The airline uses smaller aircraft ($s_i^* > s_i^{GF}$), and the reduction in seat capacity is more pronounced in the short-haul market. Furthermore, the performance of slot-rescue flights creates a denser route network. As a result, departure and arrival times are closer to passenger preferences, implying an increased network benefit. Consequently, passenger demand ($q_i^* < q_i^{GF}$) and airfares ($p_i^* < p_i^{GF}$) are higher under a grandfather policy. The grandfather policy reduces airline profit ($\pi^* > \pi^{GF}$) as a result of the negative marginal profit from slot-rescue flights, but increases passenger surplus ($CS^* < CS^{GF}$), since they benefit from higher flight frequencies. If $c < \tau$, the airport profit increases with each additional passenger. As the grandfather policy and the operation of slot-rescue flights increase passenger volume, airport profit, as long as $c < \tau$, increases as well. If $c = \tau$, the airport profit does not change, but equals a loss of the fixed airport costs F.

In the next step we compare the welfare in a situation with a grandfather policy in place, to the case of no grandfather policy. In order to do this, we assume that conditions 3 and 4 hold and we are in Area II. Total welfare is determined as the sum of airline profit, passenger surplus, and airport profit, for both a monopoly market with a slot-coordinated airport (W^{GF}) and a non-capacity-constrained airport (W^*) (see Appendix .D).

PROPOSITION 5: *Let*

$$\Delta_W(\theta) = W^{GF}(\theta) - W^*$$

then for $\tilde{\theta} < \theta \leq 1$

$$\Delta_W(\tilde{\theta}) = 0, \ \textit{and} \ \frac{\partial \Delta_W}{\partial \theta}_{|\theta=\tilde{\theta}} > 0.$$

Furthermore, $\partial^2 \Delta_W / \partial \theta^2 = \textit{const.}$ *and if*

$$k_A > \frac{(\gamma^2 - 4bk_B)\sqrt{(8b^2k_B^2 - \gamma^4)}}{2b\sqrt{2}(8bk_B - 3\gamma^2)} - \frac{(\gamma^2 - 2bk_B)^2}{b(8bk_B - 3\gamma^2)} = \underline{\underline{k_A}}, \ \textit{then} \ \frac{\partial^2 \Delta_W}{\partial \theta^2} < 0.$$

A grandfather policy has no effect on total welfare, if slot minimum usage $\tilde{\theta}\overline{M}$ equals optimal frequency f^*, i.e. $\Delta_W(\tilde{\theta}) = 0$. In this case, an airline does not have to perform slot-rescued flights, and can stay with the non-constricted flight network strategy. When $\theta > \tilde{\theta}$, the use-it-or-lose-it rule is binding and the effect on total welfare is initially positive, since the sum of passenger surplus and airport profit from slot-rescue flights exceed the airline profit loss. Furthermore, the second derivate is constant and if $k_A > \underline{\underline{k_A}}$, which applies in Area II, the second derivate is negative. That implies that Δ_W is decreasing in θ and may become negative. Considering that $\theta \leq 1$, the negative welfare effect occurs only if the unconstrained airline operates a number of flights that is small, compared to the airport capacity. Thus, the negative marginal profits of slot-rescue flights can no longer be compensated for by the increase in passenger surplus and airport profit. Figure 3 is a contour plot of the welfare difference and displays positive (green) and negative (red) contour lines of the Δ_W function, depending on the use-it-fraction θ and the ratio of declared airport capacity $\overline{M}$ to optimal flight frequency f^*.

Compared to a welfare-maximizing supply, a monopolistic supplier of passenger air traffic increases prices and decreases flight frequency. This market distortion can be moderated through a use-it-or-lose-it rule, if the rule is binding and induces additional flights. However, it is unclear whether the use-it-or-lose-it rule only binds in extraordinary circumstances, such as a negative demand shock, or is a common phenomenon. Furthermore, as our model consists of specific assumptions, and most airports are served by more than one airline, the welfare result of this paper should be interpreted with caution. To get the full picture we refer to the ongoing scholarly debate surveyed by Zhang and Czerny (2012) and Gillen

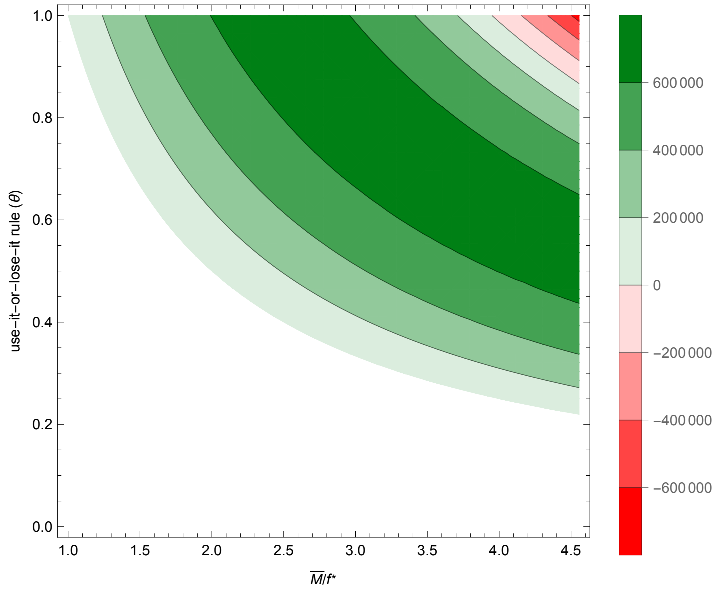

Figure 3. : Welfare effects of a grandfather policy in a monopoly market

Parameter values are:

$\omega_A = 300, \omega_B = 600, \gamma = 10, \tau = 10, b = 0.101, k_A = 500, k_B = 800, c = 5, F = 10000, \overline{M} = 250.$

et al. (2016).[4]

Now, we consider how a social planner would design a welfare-maximizing airline network, under the condition that the same number of flights as the monopolistic airline are offered to fulfill the use-it-or-lose-it rule. Welfare-maximizing frequencies are (see Appendix .E)

$$f_i^{SP} = \frac{\theta\overline{M}(2bk_j - \gamma^2) + \gamma(\omega_i - \omega_j)}{2(b(k_i + k_j) - \gamma^2)}.$$

At a given $\theta > \tilde{\theta}$, the social planner chooses the same number of total flights as the monopolistic airline, i.e. $f^* < f^{GF} = f^{SP}$. If $\tilde{\theta} < \theta < \hat{\theta}$, the monopolistic airline oversupplies the short-haul market $f_A^{SP} < f_A^{GF}$, whereas the long-haul market is undersupplied $f_B^{SP} > f_B^{GF}$. A social planner would supply less short-haul flights and more long-haul flights.

In conclusion, a grandfather policy can motivate airlines performing slot-rescue flights to prevent the loss of slots. The additional flights may increase welfare. Furthermore, we observe a distortion of the airline route network. To rescue slots, the airline bias its route network towards short-haul distances.

---

[4] See also Rassenti et al. (1982), Starkie (1994, 1998), Czerny (2008), Brueckner (2009), Basso and Zhang (2010), Czerny (2010), Fukui (2010), Sieg (2010), Fukui (2012), Swaroop et al. (2012), Zografos et al. (2012), Chen and Solak (2014), Fukui (2014), Jacquillat and Odoni (2015), Sheng et al. (2015), Pyrgiotis and Odoni (2016), Jacquillat et al. (2017), Zografos et al. (2017), Ribeiro et al. (2018), Czerny and Lang (2019), Fukui (2019), Czerny (2020), de Palma and Lindsey (2020) and Lang and Czerny (2022a,b).

III. Grandfather policy during COVID-19

The COVID-19 outbreak caused a significant decline in air traffic movements by up to 68 % in March and April 2020, compared to the corresponding period in 2019 (Eurocontrol, 2022). Figure 4 illustrates the number of slots used per month at slot-coordinated European airports and the use-it-or-lose-it threshold during each scheduling period. As a consequence of the sudden demand shock and government-imposed COVID-19-related measures, the EU Commission delegated several amendments to Council Regulation (EEC) No.95/93 (see Table 1), to specifically avoid slot-rescue flights. During the summer season 2020 and winter season 2020/21, the use-it-or-lose-it rule (80/20 rule) was suspended.

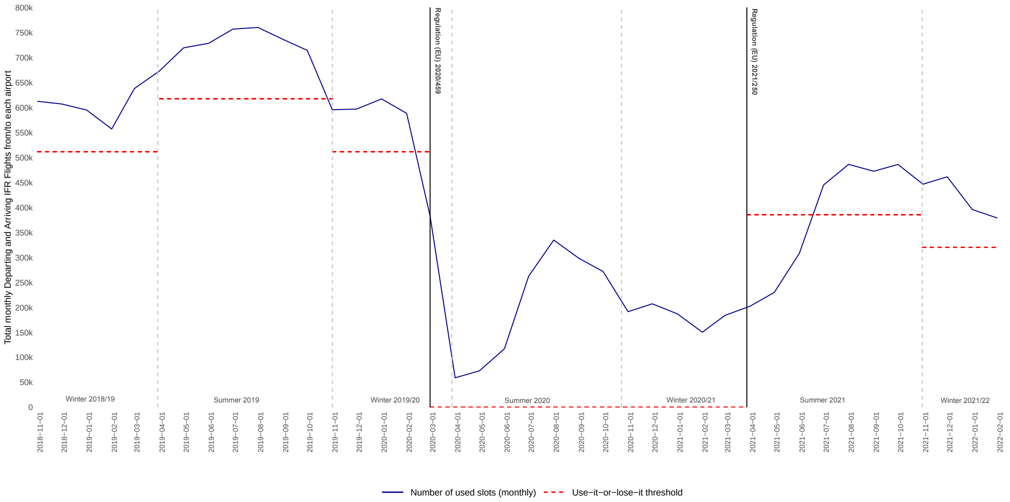

Figure 4. : Monthly slot usage of selected slot-coordinated airports

The figure plots the monthly aircraft movements from and to over 30 slot-coordinated airports in the European aviation region, which incorporates the entire EU as well as Turkey and Russia. To calculate the thresholds of minimum slot usage, we assume that the maximum monthly aircraft movements for each airport in each pre-COVID-19 scheduling period reflect nearly 100 % slot series usage.

As air traffic began to recover in summer 2021, and travel restrictions were abolished, the EU decided on a more limited relief for airport slot management within the EU (see Figure 4). Airlines received a full exemption of the use-it-or-lose-it rule of up to 50 % of their slot series at an airport, provided they were returned to the coordinator before February 28, 2021. During the summer season 2021 and winter season 2021/22, the use-it-or-lose-it threshold was reduced to 50 % (50/50). If government COVID-19-related measures restrict flight operations on certain routes, airlines can request a justified non-use of slots. Furthermore, the regulation entitles the EU Commission to respond to pandemic developments by adjusting the slot usage rate between 30 % and 70 %. For the summer season 2022, the use-it-or-lose-it threshold is reduced to 64 % (64/36). Increasing the use-it-or-lose-it threshold from 50/50 to 64/36 may be optimal for the current situation, but will affect airlines' strategic behavior if demand weakens again. Demand and travel restrictions are heterogeneous throughout Europe. Homogenous regulation would thus not be able to handle this heterogeneity. If the required threshold is too high for an airline at an airport, the airline uses slot-rescue flights to maintain

Table 1—: Overview of slot regulation during the COVID-19 pandemic

From	To	Slot Regulation	Legislative Act
March 30, 2020	October 24, 2020	• Suspension of the use-it-or-lose-it rule from March 1, 2020 to October 24, 2020 and can be prolonged if there is evidence that the decline in air traffic due to the COVID-19 pandemic continues. • Unused slot series of this period shall be returned to the coordinator for reallocation to other airlines.	Regulation (EU) 2020/459 of March 30, 2020
October 25, 2020	March 27, 2021	• Suspension of the use-it-or-lose-it rule is prolonged to March 27, 2021.	Regulation (EU) 2020/1477 of October 14, 2020
March 28, 2021	March 26, 2022	• Use-it-or-lose-it threshold of 50 % (50/50) of the slot series. • Full exemption of up to 50 % of the slot series at an airport, provided they were returned to the coordinator before February 28, 2021. Temporarily, these slot series can be reallocated by the coordinator to other airlines for the summer schedule 2021, but will be returned to the airline in the following summer schedule 2022. • Implementation of the 'justified non-use of slots' (JNUS) exemption, which protects airlines' historic rights to slot series when sustainable operations are not possible due to government-imposed COVID-19-related measures. • The EU Commission is empowered to respond to COVID-19 pandemic developments by adjusting the slot utilization rate between a range of 30 % to 70 %.	Regulation (EU) 2021/250 of February 16, 2021
March 27, 2022	October 29, 2022	• Use-it-or-lose-it threshold of 64 % (64/36) of the slot series. • Extention of the JNUS exemption.	Regulation (EU) 2022/255 of 15 December 2021

The amendments of Council Regulation (EEC) No 95/93 due to the COVID-19-pandemic are given in European Union (2021a, 2020, 2021b, 2022).

its slot series.

IV. Climate effects of slot hoarding

The emission of greenhouse gases in the aviation sector is tackled by two major schemes: The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and the EU Emissions Trading Scheme (EU ETS). However, flights affect the environment differently, depending, amongst other factors, on the distance, the aircraft type, and whether emissions are handled in the EU ETS or CORSIA. The latter is determined by flight origin and destination. Accordingly, and as suggested by our model results (see Section II.C), differentiating between slot-rescue flights on short-haul and long-haul distances, or domestic and international distances, is crucial to demonstrating potential asymmetric environmental effects.

A. The EU ETS

The EU ETS is a cap-and-trade system that in particular integrates the emissions of stationary power-generation plants and energy-intensive industries, and, since 2012, the aviation sector is included. In general, there are two types of emission allowances: European Union Allowances (EUAs) for stationary installations and the European Union Aviation Allowances (EUAAs) for the aviation sector.

From 2013 to 2020 (phase 3), the cap in aviation was kept constant at 95 % of the historical average aviation emissions of 2004-2006. Since 2021 (phase 4), the cap declines annually by a factor of 2.2 % (European Union, 2017). Participating aircraft operators receive a total of 82 % of EUAAs for free, 15 % are auctioned and 3 % are held back, e.g. for new entrants (European Union, 2009). Furthermore, unused allowances issued after January 1, 2013 are valid for an unlimited period of time and can be transferred to subsequent periods (European Union, 2018). As a result of the sudden demand shock and government-imposed measures related to the COVID-19 pandemic, airlines surrendered less than their allocated emission allowances (EUAAs) (EEA, 2021). However, airlines can hoard their unused allowances for future flights, since they do not expire.

If aviation sector demand for EUAAs exceeds its supply, as in pre-COVID-19 years, aircraft operators are able to purchase and surrender allowances of the stationary sector (EUAs) as well. While in phase 3, EUAAs could only be sold to other airlines, from phase 4 onwards, operators of stationary installations can also purchase EUAAs.

The EU ETS considers all flights conducted by European and non-European airlines within the European Economic Area (EEA), including domestic flights[5] (European Union, 2009). The scope of the EU ETS is shown in Figure 5. Most flights within the EEA, both domestic and international, can be classified as short-haul or at most medium-haul. By contrast, flights between EEA and non-EEA countries, i.e. short-haul flights crossing the EU border or particularly intercontinental long-haul flights, are not within the scope of the EU ETS, and therefore are not compensated.

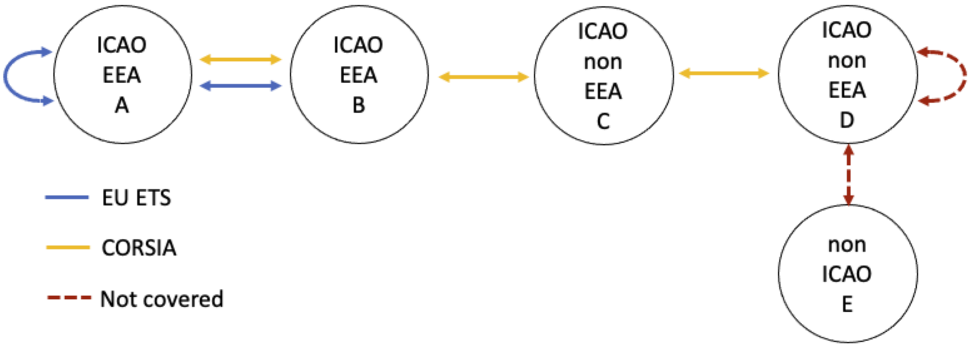

Figure 5. : Scope of the EU ETS and CORSIA from 2027 onwards

---

[5] An extension of the EU ETS to international flights to and from non-EEA countries is being discussed in a proposal for a Directive of the European Parliament and of the Council e.g. ICCT (2021).

As suggested by our model, an airline operates slot-rescue flights in particular as short-haul within the EEA. Airlines need the corresponding allowances, either EUAs or EUAAs. Thus, CO_2 emissions are abated elsewhere, either in the aviation sector or at stationary installations. Climate damage caused by slot hoarding on intra-European routes is therefore almost entirely prevented by the EU ETS.

B. CORSIA

Compared to the EU ETS, CORSIA is a global CO_2 compensation scheme exclusively designed for the aviation sector. CORSIA was adopted in 2016 to achieve carbon-neutral aviation growth with respect to an average baseline emissions level. Initially, this level was based on 2019 and 2020 emissions. The COVID-19 pandemic, however, lead to a sharp decline in air traffic. This lowered the CORSIA baseline level significantly, resulting in a greater compensation burden for airlines. As a consequence, ICAO decided to adjust the baseline level to 2019 emissions (ICAO, 2020).

The growth in CO_2 emissions, i.e. only flight emissions exceeding the baseline, could then be offset through the purchase of eligible emission units. CORSIA includes three implementation phases. Although participation in the pilot phase (2021-2023) and the first phase (2024-2026) is voluntary, over 100 states participate in CORSIA, including e.g. all EEA-states and the United States (ICAO, 2021, 2018). In the second phase (2027-2035), participation will be mandatory for all ICAO member states. Furthermore, CORSIA relies on a route-based approach and only considers international flights between ICAO member states.[6] Only flight emissions additional to the baseline level will be offset. Flights within an ICAO member state, i.e. domestic flights, or those between an ICAO member state to an ICAO member state that is not currently participating or to a non-ICAO member state, are not covered. For international flights within the EEA, the EU ETS and CORSIA overlap (see Figure 5). Therefore, the EU Commission is discussing an appropriate coexistence of both schemes to avoid double charging (ICF Consulting et al., 2020).

With respect to our model, a binding use-it-or-lose-it rule biases the airline route network in favor of short-haul flights. In large countries with high domestic air traffic demand, slot-rescue flights may be operated on domestic routes. This applies in particular to countries such as the USA or China, where domestic flights account for more than 90 % of all departures (Graver et al., 2020). However, CORSIA does not account for domestic flights. Thus, greenhouse gases emitted by slot-rescue flights in domestic markets are never offset. Despite both the United States and China being ICAO member states, China does not participate in CORSIA yet, which means that even emissions from international flights, to and from China, will not be covered by CORSIA until 2027 (ICAO, 2021).

Since the aviation market has not yet fully recovered (see Figure 4), there is no emissions growth compared to the pre-COVID-19 year. Consequently, no aviation emissions have yet been offset by CORSIA. To summarize, CORSIA is neither ambitious nor strict (ICF Consulting et al., 2020) in general, but especially for slot-rescue flights considered in this paper, rather ineffective.

---

[6] Exempted are aircraft operators emitting less than 10,000 metric tons on international flights between ICAO member states; emissions from small aircraft with a maximum take-off mass of less than 5,700 kg; as well as medical, humanitarian, or firefighting flights.

V. Conclusion

A grandfather policy at slot-controlled airports may motivate incumbent airlines to hoard slots, in order to prevent potential newcomers from entering the airport and reinforcing incumbent airlines' market power. Flights serving only a small number of passengers, or no passengers at all, operated purely to rescue slots, received considerable publicity during the COVID-19 pandemic.

Our approach allows a monopolistic airline to choose both short-haul and long-haul flights when deciding on its route network at a slot-coordinated airport. We show that this airline's route network can be distorted by a grandfather policy. A binding use-it-or-lose-it rule induces the airline to fly more on both markets, but especially slot-rescue flights on short-haul distances. Slot-rescue flights densify the airline route network, benefiting consumers and thus increase passenger volume, which generates higher passenger fees for the airport. However, the operation of each slot-rescue flight reduces the airline's profit. Consequently, slot-rescue flights can be either welfare-increasing or welfare-decreasing. This relies on the design of the use-it-or-lose-it rule, and the ratio of profit-maximizing frequencies to declared airport capacity. It should be noted that our results and welfare analysis are limited by specific model assumptions, such as a greater willingness to pay for long-haul flights, a linear demand function and a monopolistic airline market. Furthermore, the implementation in future research of transit passengers and the role of slot-rescue flights as feeder-flights could enrich the analysis of slot-hoarding behavior. In addition, little research has been conducted to determine the actual contribution of slot-rescue flights to overall flight volume. Whether slot-rescue flights are therefore a common phenomenon, or occur as a consequence of extraordinary shocks, has not yet been answered, and provides an opportunity for further research.

Air traffic emits greenhouse gases and fosters climate change. Such climate damage is tackled by the EU ETS and CORSIA. The climate damage from slot-rescue flights depend on the origin and destination and which scheme applies to this flight route. Therefore, a distinction between short- and long-haul slot-rescue flights, or domestic and international ones, is necessary. Climate damage from slot-rescue flights within the EU is considered by the EU ETS, and consequently these emissions are abated elsewhere, either in the aviation sector or at stationary installations. CORSIA, on the other hand, only covers international flights between ICAO member states. In large countries, slot-rescue flights are mostly short-haul and identified as domestic flights, which are not subject to CORSIA. To summarize, CORSIA is rather ineffective for slot-rescue flights, while the EU ETS prevents additional climate damage. As long as grandfather rules generate slot-rescue flights, the inability to protect the climate adds to the list of CORSIA's drawbacks. CORSIA should not, even if it is intended to be so, become the global compensation scheme. Rather, policy makers should try to establish a system that covers all flights, even non-additional and domestic. Should CORSIA become the global system, our model supports the recommendation of Maertens et al. (2019) and ICF Consulting et al. (2020), to continue the EU ETS for national and intra-EEA flights. Otherwise, there would be no emission compensation for domestic flights, including domestic slot-rescue flights within the EEA, and the climate damage from aviation would be significantly amplified.

Acknowledgements and Statements

The authors would like to thank Sebastian Badura, Xenia Breiderhoff, Maria Kennel, Alina Krämer, Edita Selimaj and Sebastian Specht for their valuable research assistance; and Brian Bloch for his editing of the English. We also thank Christina Brand and Jan Wessel for helpful comments. Finally, we would like to thank the editor of this special issue, two anonymous referees, the guest editor and participants of the 2022 International Transportation Economics Association Conference for their helpful comments in improving this paper.

Funding: none.

Declaration of interest: none.

Appendices

A. *Proof of Proposition 1*

Proof for frequencies ($f_A^* > f_B^*$)

$$
\begin{aligned}
&k_A < \frac{4bk_B(\omega_A - \tau) + \gamma^2(\omega_B - \omega_A)}{4b(\omega_B - \tau)} \\
&\iff 4bk_A(\omega_B - \tau) < 4bk_B(\omega_A - \tau) + \gamma^2(\omega_B - \omega_A) \\
&\iff 4bk_A\omega_B - 4bk_A\tau - \gamma^2\omega_B + \gamma^2\tau < 4bk_B\omega_A - 4bk_B\tau - \gamma^2\omega_A + \gamma^2\tau \\
&\iff (\omega_B - \tau)(4bk_A - \gamma^2) < (\omega_A - \tau)(4bk_B - \gamma^2) \\
&\iff \frac{\gamma(\omega_B - \tau)}{4bk_B - \gamma^2} < \frac{\gamma(\omega_A - \tau)}{4bk_A - \gamma^2} \\
&\iff \frac{\gamma(\omega_B - \tau)}{\xi_B} < \frac{\gamma(\omega_A - \tau)}{\xi_A} \\
&\iff f_B^* < f_A^*, \quad \text{q.e.d.}
\end{aligned}
$$

B. *Proof of Proposition 2*

Proof for passenger demand ($q_A^* < q_B^*$)

$$
\begin{aligned}
&k_A > \frac{\gamma^2 k_B(\omega_B - \tau)}{4bk_B(\omega_B - \omega_A) + \gamma^2(\omega_A - \tau)} \\
&\iff 4bk_Bk_A\omega_B - 4bk_Bk_A\omega_A + \gamma^2k_A\omega_A - \gamma^2k_A\tau > \gamma^2k_B\omega_B - \gamma^2k_B\tau \\
&\iff 4bk_Bk_A\omega_B - 4bk_Bk_A\tau + \gamma^2k_B\tau - \gamma^2k_B\omega_B > 4bk_Bk_A\omega_A - 4bk_Bk_A\tau + \gamma^2k_A\tau - \gamma^2k_A\omega_A \\
&\iff 4bk_Bk_A(\omega_B - \tau) - \gamma^2k_B(\omega_B - \tau) > 4bk_Bk_A(\omega_A - \tau) - \gamma^2k_A(\omega_A - \tau) \\
&\iff k_B(\omega_B - \tau)(4bk_A - \gamma^2) > k_A(\omega_A - \tau)(4bk_B - \gamma^2) \\
&\iff \frac{2k_B(\omega_B - \tau)}{4bk_B - \gamma^2} > \frac{2k_A(\omega_A - \tau)}{4bk_A - \gamma^2} \\
&\iff \frac{2k_B(\omega_B - \tau)}{\xi_B} > \frac{2k_A(\omega_A - \tau)}{\xi_A} \\
&\iff q_B^* > q_A^*, \quad \text{q.e.d.}
\end{aligned}
$$

Proof for airfares ($p_A^* < p_B^*$)

$$
\begin{aligned}
& k_A > \frac{\gamma^2 k_B(\omega_B - \tau)}{4bk_B(\omega_B - \omega_A) + \gamma^2(\omega_A - \tau)} \\
& \iff k_A \left[4bk_B(\omega_A - \omega_B) + \gamma^2(\tau - \omega_A)\right] < \gamma^2 k_B(\tau - \omega_B) \\
& \iff 4bk_A k_B(\omega_A - \omega_B) + \gamma^2 k_A(\tau - \omega_A) < \gamma^2 k_A k_B(\tau - \omega_B) \\
& \iff 8(\omega_A - \omega_B)b^2 k_A k_B + 2\gamma^2 bk_A(\tau - \omega_A) < 2\gamma^2 bk_A k_B(\tau - \omega_B) \\
& \iff 8(\omega_A - \omega_B)b^2 k_A k_B - 2\gamma^2 bk_A(\tau + \omega_A) + 4\gamma^2 bk_A\tau < 4\gamma^2 bk_B\tau - 2\gamma^2 bk_B(\tau + \omega_B) \\
& \iff 8\omega_A b^2 k_A k_B + 8b^2 k_A k_B\tau - 2\gamma^2 bk_A(\tau + \omega_A) - 4\gamma^2 bk_B\tau + \gamma^4 b\tau < \\
& \qquad\qquad 8\omega_B b^2 k_A k_B + 8b^2 k_A k_B\tau - 4\gamma^2 bk_A\tau - 2\gamma^2 bk_B(\tau + \omega_B) + \gamma^4 b\tau \\
& \iff (2bk_A(\omega_A + \tau) - \gamma^2\tau)(4bk_B - \gamma^2) < (2bk_B(\omega_B + \tau) - \gamma^2\tau)(4bk_A - \gamma^2) \\
& \iff \frac{2bk_A(\omega_A + \tau) - \gamma^2\tau}{4bk_A - \gamma^2} < \frac{2bk_B(\omega_B + \tau) - \gamma^2\tau}{4bk_B - \gamma^2} \\
& \iff \frac{2bk_A(\omega_A + \tau) - \gamma^2\tau}{\xi_A} < \frac{2bk_B(\omega_B + \tau) - \gamma^2\tau}{\xi_B} \\
& \Leftrightarrow p_A^* < p_B^*, \quad \text{q.e.d.}
\end{aligned}
$$

C. *Proof of Proposition 3*

Proof for passenger demand ($q_A^{GF} < q_B^{GF}$):

$$
\begin{aligned}
& \overline{M} < \frac{1}{\theta}\left[\frac{(\omega_B - \omega_A)(k_A + k_B)}{\gamma(k_B - k_A)}\right] \\
& \iff \theta\overline{M}\gamma(k_B - k_A) < (\omega_B - \omega_A)(k_A + k_B) \\
& \iff \gamma\theta\overline{M}4b(k_B - k_A) < (\omega_B - \omega_A)[4b(k_A + k_B) - \gamma^2)] + (\omega_B - \omega_A)\gamma^2 \\
& \iff \gamma\theta\overline{M}[4b(k_B - k_A) - \gamma^2 + \gamma^2] + \omega_A(4bk_A - \gamma^2) + \omega_A 4bk_B - \omega_B\gamma^2 < \\
& \qquad \omega_B(4bk_B - \gamma^2) + \omega_B 4bk_A - \omega_A\gamma^2 \\
& \iff \gamma\theta\overline{M}(4bk_B - \gamma^2) - \gamma\theta\overline{M}(4bk_A - \gamma^2) + \omega_A(4bk_A - \gamma^2) + \omega_A 4bk_B - \omega_B\gamma^2 < \\
& \qquad \omega_B(4bk_B - \gamma^2) + \omega_B 4bk_A - \omega_A\gamma^2 \\
& \iff \gamma\theta\overline{M}\xi_B + \omega_A\xi_A + \omega_A 4bk_B - \omega_B\gamma^2 < \gamma\theta\overline{M}\xi_A + \omega_B\xi_B + \omega_B 4bk_A - \omega_A\gamma^2 \\
& \iff \frac{1}{2b}\left[\gamma\theta\overline{M}\frac{\xi_B}{\xi_A + \xi_B} + \omega_A\frac{\xi_A}{\xi_A + \xi_B} - \tau + \frac{\omega_A 4bk_B - \omega_B\gamma^2}{\xi_A + \xi_B}\right] < \\
& \frac{1}{2b}\left[\gamma\theta\overline{M}\frac{\xi_A}{\xi_A + \xi_B} + \omega_B\frac{\xi_B}{\xi_A + \xi_B} - \tau + \frac{\omega_B 4bk_A - \omega_A\gamma^2}{\xi_A + \xi_B}\right] \\
& \iff q_A^{GP} < q_B^{GP}, \ \text{q.e.d.}
\end{aligned}
$$

Proof for airfare ($p_A^{GF} < p_B^{GF}$):

$$
\begin{aligned}
&\overline{M} < \frac{1}{\theta}\left[\frac{(\omega_B-\omega_A)(k_A+k_B)}{\gamma(k_B-k_A)}\right] \\
&\iff \gamma\theta\overline{M}4b(k_B-k_A) - (\omega_B-\omega_A)4b(k_A+k_B) < 0 \\
&\iff \gamma\theta\overline{M}[4b(k_B-k_A)-\gamma^2+\gamma^2] - (\omega_B-\omega_A)2[2b(k_A+k_B)-\gamma^2+\gamma^2] < 0 \\
&\iff \gamma\theta\overline{M}(4bk_B-\gamma^2) - \gamma\theta\overline{M}(4bk_A-\gamma^2) - (\omega_B-\omega_A)2[2b(k_A+k_B)-\gamma^2] - \\
&\qquad 2\gamma^2(\omega_B-\omega_A) < 0 \\
&\iff \gamma\theta\overline{M}(4bk_B-\gamma^2) - \gamma\theta\overline{M}(4bk_A-\gamma^2) - (\omega_B-\tau)(4bk_A+4bk_B-2\gamma^2) + \\
&\qquad (\omega_A+\tau)(4bk_A+4bk_B-2\gamma^2) + \gamma^2(\omega_A-\omega_B) - \gamma^2(\omega_B-\omega_A) < 0 \\
&\iff \gamma\theta\overline{M}(4bk_B-\gamma^2) + (\omega_A+\tau)2[2b(k_A+k_B)-\gamma^2] + \gamma^2(\omega_A-\omega_B) < \\
&\qquad \gamma\theta\overline{M}(4bk_A-\gamma^2) + (\omega_B+\tau)2[2b(k_A+k_B)-\gamma^2] + \gamma^2(\omega_B-\omega_A) \\
&\iff (\omega_A+\tau)(\xi_A+\xi_B) + \gamma[\theta\overline{M}\xi_B + \gamma(\omega_A-\omega_B)] < \\
&\qquad (\omega_B+\tau)(\xi_A+\xi_B) + \gamma[\theta\overline{M}\xi_A + \gamma(\omega_B-\omega_A)] \\
&\iff \frac{1}{2}(\omega_A+\tau) + \frac{\gamma}{2}\left[\theta\overline{M}\frac{\xi_B}{\xi_A+\xi_B} + \frac{\gamma(\omega_A-\omega_B)}{\xi_A+\xi_B}\right] < \\
&\qquad \frac{1}{2}(\omega_B+\tau) + \frac{\gamma}{2}\left[\theta\overline{M}\frac{\xi_A}{\xi_A+\xi_B} + \frac{\gamma(\omega_B-\omega_A)}{\xi_A+\xi_B}\right] \\
&\iff p_A^{GP} < p_B^{GP}, \text{ q.e.d.}
\end{aligned}
$$

D. *Welfare analysis*

The total welfare function is defined as the sum of airline profit, passenger surplus, and airport profit. This holds for monopoly markets with a slot-coordinated airport (W^{GF}) and a non-capacity-constrained airport (W^*).
Airline profit:

$$
\begin{aligned}
&\pi^{GF}(\theta) = (p_A^{GF}(\theta)-\tau)q_A^{GF}(\theta) - k_A f_A^{GF}(\theta)^2 + (p_B^{GF}(\theta)-\tau)q_B^{GF}(\theta) - k_B f_B^{GF}(\theta)^2, \\
&\pi^* = (p_A^*-\tau)q_A^* - k_A {f_A^*}^2 + (p_B^*-\tau)q_B^* - k_B {f_B^*}^2.
\end{aligned}
$$

Passenger surplus:

$$
\begin{aligned}
CS^{GF}(\theta) &= \int_0^{q_A^{GF}(\theta)} (\omega_A - bq_A + \gamma f_A^{GF}(\theta))dq_A - p_A^{GF}(\theta)q_A^{GF}(\theta) \\
&\quad + \int_0^{q_B^{GF}(\theta)} (\omega_B - bq_B + \gamma f_B^{GF}(\theta))dq_B - p_B^{GF}(\theta)q_B^{GF}(\theta), \\
CS^* &= \int_0^{q_A^*} (\omega_A - bq_A + \gamma f_A^*)dq_A - p_A^*q_A^* + \int_0^{q_B^*} (\omega_B - bq_B + \gamma f_B^*)dq_B - p_B^*q_B^*.
\end{aligned}
$$

Airport profit, where c is the variable airport costs per passenger and F is the fixed airport costs:

$$\pi^{GF}_{Airport}(\theta) = (\tau - c)(q^{GF}_A(\theta) + q^{GF}_B(\theta)) - F \quad \text{and} \quad \pi^{*}_{Airport} = (\tau - c)(q^{*}_A + q^{*}_B) - F.$$

In order to compare the welfare in a situation with a grandfather policy in place, to the welfare in a situation without a grandfather policy, we assume that $k_A < \overline{k_A}$ (condition 3) and $k_A > \underline{k_A}$ (condition 4) hold and that we are in Area II:

$$\begin{aligned}\Delta_W(\theta) &= W^{GF}(\theta) - W^{*}\\ &= [\pi^{GF}(\theta) + \pi^{GF}_{Airport}(\theta) + CS^{GF}(\theta)] - [\pi^{*} + \pi^{*}_{Airport} + CS^{*}].\end{aligned}$$

The derivative of the welfare difference with respect to the use-it-or-lose-it rule can be written as:

$$\begin{aligned}\frac{\partial \Delta_W}{\partial \theta} =& \frac{8b^2\gamma(3k_Ak_B(\omega_A+\omega_B) + 3k_A^2(\omega_B + \gamma\theta\overline{M}) + 3k_B^2(\omega_A + \gamma\theta\overline{M}) - (k_A+k_B)^2(2c+\tau))}{8b(\gamma^2 - 2b(k_A+k_B))^2}\\ &- \frac{8b\gamma^3(\omega_A(k_A+2k_B) - \omega_B(2k_A+k_B) + (k_A+k_B)(2c+\tau-2\gamma\theta\overline{M}))}{8b\left(\gamma^2 - 2b(k_A+k_B)\right)^2}\\ &+ \frac{\gamma^5(3(\omega_A+\omega_B+\gamma\theta\overline{M}) - 2(2c+\tau)) + 8b^2k_Ak_B\theta\overline{M}(8\gamma^2 - 8b(k_A+k_B))}{8b\left(\gamma^2 - 2b(k_A+k_B)\right)^2}.\end{aligned}$$

When $\theta > \tilde{\theta}$, the use-it-or-lose-it rule is binding and we get

$$\frac{\partial \Delta_W}{\partial \theta}_{|\theta=\tilde{\theta}} > 0.$$

The second derivative is given by

$$\frac{\partial^2 \Delta_W}{\partial \theta^2} = \frac{8b^2\gamma^2(3(k_A^2+k_B^2)) + 8b^2k_Ak_B(8\gamma^2 - 8b(k_A+k_B)) - \gamma^4(16b(k_A+k_B) - 3\gamma^2)}{8b(\gamma^2 - 2b(k_A+k_B))^2}$$

and is constant.
If

$$k_A > \frac{(\gamma^2 - 4bk_B)\sqrt{(8b^2k_B^2 - \gamma^4)}}{2b\sqrt{2}(8bk_B - 3\gamma^2)} - \frac{(\gamma^2 - 2bk_B)^2}{b(8bk_B - 3\gamma^2)} = \underline{\underline{k_A}}, \text{ then } \frac{\partial^2 \Delta_W}{\partial \theta^2} < 0.$$

E. *Airline network of the social planner*

Let the welfare function of the social planner be defined as

$$W^{SP} = \pi^{SP}(\theta) + \pi^{SP}_{Airport}(\theta) + CS^{SP}(\theta).$$

Subject to the use-it-or-lose-it rule

$$\theta\overline{M} \leq \sum f_i,$$

the Lagrangian function is defined by

$$\begin{aligned}
\mathcal{L}(f_A, f_B, q_A, q_B, \lambda) =& [q_A(\omega_A - bq_A + \gamma f_A - \tau)] - k_A f_A^2 \\
&+ [q_B(\omega_B - bq_B + \gamma f_B - \tau)] - k_B f_B^2 \\
&+ \int_0^{q_A} (\omega_A - bq_A + \gamma f_A)\, dq_A - q_A(\omega_A - bq_A + \gamma f_A) \\
&+ \int_0^{q_B} (\omega_B - bq_B + \gamma f_B)\, dq_B - q_B(\omega_B - bq_B + \gamma f_B) \\
&+ (\tau - c)(q_A + q_B) - F \\
&- \lambda(\theta M - f_A - f_B).
\end{aligned}$$

The corresponding Lagrangian conditions are as follows

$$\begin{aligned}
\tfrac{\partial \mathcal{L}}{\partial f_i} &= \gamma q_i - 2f_i k_i + \lambda = 0 \Rightarrow f_i = \tfrac{\gamma q_i + \lambda}{2k_i}, \\
\tfrac{\partial \mathcal{L}}{\partial q_i} &= \omega_i + \gamma f_i - bq_i - c = 0 \Rightarrow q_i = \tfrac{\omega_i + \gamma f_i - c}{b}, \\
\tfrac{\partial \mathcal{L}}{\partial \lambda} &= f_i + f_j - \theta\overline{M} = 0 \Rightarrow \theta\overline{M} = f_i + f_j.
\end{aligned}$$

By solving the system of FOCs, we obtain the welfare-maximizing frequencies for both markets:

$$\begin{aligned}
f_A^{SP} &= \frac{\theta\overline{M}(2bk_B - \gamma^2) + \gamma(\omega_A - \omega_B)}{2(b(k_A + k_B) - \gamma^2)}, \\
f_B^{SP} &= \frac{\theta\overline{M}(2bk_A - \gamma^2) + \gamma(\omega_B - \omega_A)}{2(b(k_A + k_B) - \gamma^2)}.
\end{aligned}$$

Rewrite condition 10 as

$$\hat{\theta} = \frac{1}{\overline{M}} \left[\frac{(\omega_B - \omega_A)(k_A + k_B))}{\gamma(k_B - k_A)} \right].$$

Comparing the airline network of a social planner with the airline network of a monopolistic airline, we get

$$f_A^{SP} < f_A^{GF} \quad \text{and} \quad f_B^{SP} > f_B^{GF}$$

if $\underline{k_A} < k_A < \overline{k_A}$ and $\tilde{\theta} < \theta < \hat{\theta}$.

REFERENCES

ACI, IATA, and WWACG (2020). Worldwide airport slot guidelines. Last accessed on 26 April 2022.

Adler, N. (2005). Hub-spoke network choice under competition with an application to western europe. *Transportation Science*, 39(1):58–72.

Adler, N., Fu, X., Oum, T. H., and Yu, C. (2014). Air transport liberalization and airport slot allocation: The case of the northeast asian transport market. *Transportation Research Part A: Policy and Practice*, 62:3–19.

Álvarez-Sanjaime, Ó., Cantos-Sánchez, P., Moner-Colonques, R., and Sempere-Monerris, J. J. (2020). A three-stage competition game in an air transport network under asymmetric valuation of flight frequencies. *Economics of Transportation*, 21:100141.

Anger, A. (2010). Including aviation in the european emissions trading scheme: Impacts on the industry, CO2 emissions and macroeconomic activity in the EU. *Journal of Air Transport Management*, 16(2):100–105.

Barbot, C. (2004). Economic effects of re-allocating airports slots: a vertical differentiation approach. *Journal of Air Transport Management*, 10(5):333–343.

Basso, L. J. and Zhang, A. (2010). Pricing vs. slot policies when airport profits matter. *Transportation Research Part B: Methodological*, 44(3):381–391.

Brueckner, J. K. (2004). Network structure and airline scheduling. *The Journal of Industrial Economics*, 52:291–312.

Brueckner, J. K. (2009). Price vs. quantity-based approaches to airport congestion management. *Journal of Public Economics*, 93(5-6):681–690.

Button, K. (2020). Studying the empirical implications of the liberalization of airport markets. *Competition and Regulation in Network Industries*, 21(3):223—243.

Chen, H. and Solak, S. (2014). Lower cost arrivals for airlines: Optimal policies for managing runway operations under optimized profile descent. *Production and Operations Management*, 24(3):402–420.

Czerny, A. I. (2008). Congestion management at airports under uncertainty. *Airport Slots: International Experiences and Options for Reform, Ashgate.*

Czerny, A. I. (2010). Airport congestion management under uncertainty. *Transportation Research Part B: Methodological*, 44(3):371–380.

Czerny, A. I. (2020). *Optimal Use-it-or-lose-it Rules for Airport Slot Management.*

Czerny, A. I. and Lang, H. (2019). A pricing versus slots game in airport networks. *Transportation Research Part B: Methodological*, 125:151–174.

D'Alfonso, T., Jiang, C., and Bracaglia, V. (2016). Air transport and high-speed rail competition: Environmental implications and mitigation strategies. *Transportation Research Part A: Policy and Practice*, 92:261–276.

de Palma, A. and Lindsey, R. (2020). Tradable permit schemes for congestible facilities with uncertain supply and demand. *Economics of Transportation*, 21:100149.

de Wit, J. and Burghouwt, G. (2008). Slot allocation and use at hub airports, perspectives for secondary trading. *European Journal of Transport and Infrastructure Research*, 8(2):147–164.

EEA (2021). Eu emissions trading system (ets) data viewer. Last accessed on 26 April 2022.

Efthymiou, M. and Papatheodorou, A. (2019). EU emissions trading scheme in aviation: Policy analysis and suggestions. *Journal of Cleaner Production*, 237:117734.

Eurocontrol (2022). Daily traffic variation - states. Last accessed on 26 April 2022.

European Parliament, Directorate-General for Internal Policies of the Union, and Lenoir, Nathalie (2016). *Airport slots and aircraft size at EU airports: in-depth analysis: research for TRAN Committee.* European Parliament.

European Union (2009). Directive 2008/101/ec of the european parliament and of the council of 19 november 2008 amending directive 2003/87/ec so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the community. *Official Journal of the European Union*, L 8:3–21.

European Union (2017). Regulation (eu) 2017/2392 of the european parliament and of the council of 13 december 2017 amending directive 2003/87/ec to continue current limitations of scope for aviation activities and to prepare to implement a global market-based measure from 2021. *Official Journal of the European Union*, L 350:7–14.

European Union (2018). Directive (eu) 2018/410 of the european parliament and of the council of 14 march 2018 amending directive 2003/87/ec to enhance cost-effective emission reductions and low-carbon investments, and decision (eu) 2015/1814. *Official Journal of the European Union*, L 76:3–27.

European Union (2020). Commission delegated regulation (eu) 2020/1477 of 14 october 2020 amending council regulation (eec) no 95/93 as regards the temporary extension of exceptional measures to address the consequences caused by the covid-19 pandemic (text with eea relevance). *Official Journal of the European Union*, L 338:4–6.

European Union (2021a). Regulation (eu) 2020/459 of the european parliament and of the council of 30 march 2020 amending council regulation (eec) no 95/93 on common rules for the allocation of slots at community airports (text with eea relevance). *Official Journal of the European Union*, L 99:1–4.

European Union (2021b). Regulation (eu) 2021/250 of the european parliament and of the council of 16 february 2021 amending council regulation (eec) no 95/93 as regards temporary relief from the slot utilisation rules at union airports due to the covid-19 crisis (text with eea relevance). *Official Journal of the European Union*, L 58:1–8.

European Union (2022). Commission delegated regulation (eu) 2022/255 of 15 december 2021 amending council regulation (eec) no 95/93 as regards the extension of measures for temporary relief from the slot utilisation rules due to the covid-19 crisis. *Official Journal of the European Union*, L 42:1–4.

FAA (2022). Slot administration - regulatory information. Last accessed on 26 April 2022.

Flores-Fillol, R. (2009). Airline competition and network structure. *Transportation Research Part B: Methodological*, 43(10):966–983.

Forsyth, P. (2007). The impacts of emerging aviation trends on airport infrastructure. *Journal of Air Transport Management*, 13(1):45–52.

Frankfurter Allgemeine Zeitung (2021). Wir müssen 33.000 flüge streichen. Last accessed on 26 April 2022.

Fu, X., Oum, T. H., Chen, R., and Lei, Z. (2015). Dominant carrier performance and international liberalization – the case of northeast asia. *Transport Policy*, 43:61–75.

Fukui, H. (2010). An empirical analysis of airport slot trading in the united states. *Transportation Research Part B: Methodological*, 44(3):330–357.

Fukui, H. (2012). Do carriers abuse the slot system to inhibit airport capacity usage? evidence from the us experience. *Journal of Air Transport Management*, 24:1–6.

Fukui, H. (2014). Effect of slot trading on route-level competition: Evidence from experience in the UK. *Transportation Research Part A: Policy and Practice*, 69:124–141.

Fukui, H. (2019). How do slot restrictions affect airfares? new evidence from the US airline industry. *Economics of Transportation*, 17:51–71.

Gillen, D., Jacquillat, A., and Odoni, A. R. (2016). Airport demand management: The operations research and economics perspectives and potential synergies. *Transportation Research Part A: Policy and Practice*, 94:495–513.

Graver, B., Rutherford, D., and Zheng, S. (2020). *CO2 emissions from Commercial Aviation 2013, 2018, and 2019.* The International Council on Clean Transportation.

Heimer, O. and Shy, O. (2006). Code-sharing agreements, frequency of flights, and profits under parallel operation. In Lee, Darin, editor, *Advances in Airline Economics*, number 1, pages 163–181. Elsevier, Amsterdam.

ICAO (2018). Annex 16 to the convention of internation civil aviation - volume iv, carbon offsetting an reduction schemefor international aviation. Last accessed on 26 April 2022.

ICAO (2020). Icao council agrees to the safeguard adjustment for corsia in light of covid-19 pandemic. Last accessed on 26 April 2022.

ICAO (2021). Corsia states for chapter 3 state pairs. Last accessed on 26 April 2022.

ICCT (2021). *International Council on Clean Transportation consultation response on Proposal for a Directive of the European Parliament and of the Council - amending Directive 2003/87/EC as regards aviation's contribution to the Union's economy-wide emission reduction target and appropriately implementing a global market-based measure.*

ICF Consulting, Air Transportation Analytics , NewClimate Institute, Cambridge Econometrics, HFW, and Starckx, S. (2020). Assessment of icao's global market-based measure (corsia) pursuant to article 28b and for studying cost pass- through pursuant to article 3d of the eu ets directive. Last accessed on 26 April 2022.

IPCC (1999). Aviation and the global atmosphere: A special report of ipcc working groups i and iii. Last accessed on 2 May 2022.

Jacquillat, A. and Odoni, A. R. (2015). An integrated scheduling and operations approach to airport congestion mitigation. *Operations Research*, 63(6):1390–1410.

Jacquillat, A., Odoni, A. R., and Webster, M. D. (2017). Dynamic control of runway configurations and of arrival and departure service rates at JFK airport under stochastic queue conditions. *Transportation Science*, 51(1):155–176.

Kleit, A. N. and Kobayashi, B. H. (1996). Market failure or market efficiency? evidence on airport slot usage. *Research in Transportation Economics*, 4(C):1–32.

Lang, H. and Czerny, A. I. (2022a). Airport pricing versus (grandfathered) slots: A generalization. *Economics of Transportation*, 29:100249.

Lang, H. and Czerny, A. I. (2022b). How (grandfathered) slots can be a first-best policy for a congested airport whereas prices cannot. *Journal of Transport Economics and Policy (JTEP)*, 56(2):217–242.

Madas, M. A. and Zografos, K. G. (2008). Airport capacity vs. demand: Mismatch or mismanagement? *Transportation Research Part A: Policy and Practice*, 42(1):203–226.

Maertens, S., Grimme, W., Scheelhaase, J. D., and Jung, M. (2019). Options to continue the eu ets for aviation in a corsia-world. *Sustainability*, 11(20):1–19.

Malina, R., McConnachie, D., Winchester, N., Wollersheim, C., Paltsev, S., and Waitz, I. A. (2012). The impact of the european union emissions trading scheme on US aviation. *Journal of Air Transport Management*, 19:36–41.

Miranda, V. A. P. and Oliveira, A. V. M. (2018). Airport slots and the internalization of congestion by airlines: An empirical model of integrated flight disruption management in brazil. *Transportation Research Part A: Policy and Practice*, 116:201–219.

Morisset, T. and Odoni, A. (2011). Capacity, delay, and schedule reliability at major airports in europe and the united states. *Transportation Research Record: Journal of the Transportation Research Board*, 2214(1):85–93.

Oum, T. H., Zhang, A., and Zhang, Y. (1995). Airline network rivalry. *The Canadian Journal of Economics*, 28(4a):836–857.

Pels, E. (2008). Airline network competition: Full-service airlines, low-cost airlines and long-haul markets. *Research in Transportation Economics*, 24(1):68–74. The Economics of Low Cost Airlines.

Pyrgiotis, N. and Odoni, A. (2016). On the impact of scheduling limits: A case study at newark liberty international airport. *Transportation Science*, 50(1):150–165.

Rassenti, S. J., Smith, V. L., and Bulfin, R. L. (1982). A combinatorial auction mechanism for airport time slot allocation. *The Bell Journal of Economics*, 13(2):402.

Ribeiro, N. A., Jacquillat, A., Antunes, A. P., Odoni, A. R., and Pita, J. P. (2018). An optimization approach for airport slot allocation under IATA guidelines. *Transportation Research Part B: Methodological*, 112:132–156.

Ryley, T., Baumeister, S., and Coulter, L. (2020). Climate change influences on aviation: A literature review. *Transport Policy*, 92:55–64.

Scheelhaase, J., Grimme, W., and Schaefer, M. (2010). The inclusion of aviation into the EU emission trading scheme – impacts on competition between european and non-european network airlines. *Transportation Research Part D: Transport and Environment*, 15(1):14–25.

Scheelhaase, J. and Maertens, S. (2020). How to improve the global 'carbon offsetting and reduction scheme for international aviation' (CORSIA)? *Transportation Research Procedia*, 51:108–117.

Scheelhaase, J., Maertens, S., and Grimme, W. (2021). Options for improving the EU emissions trading scheme (EU ETS) for aviation. *Transportation Research Procedia*, 59:193–202.

Scheelhaase, J. D., Maertens, S., Grimme, W., and Jung, M. (2018). Eu ets versus corsia – a critical assessment of two approaches to limit air transport's co2 emissions by market-based measures. *Journal of Air Transport Management*, 67:55–62.

Sheng, D., Li, Z.-C., bin Xiao, Y., and Fu, X. (2015). Slot auction in an airport network with demand uncertainty. *Transportation Research Part E: Logistics and Transportation Review*, 82:79–100.

Sheng, D., Li, Z.-C., and Fu, X. (2019). Modeling the effects of airline slot hoarding behavior under the grandfather rights with use-it-or-lose-it rule. *Transportation Research Part E: Logistics and Transportation Review*, 122:48–61.

Sieg, G. (2010). Grandfather rights in the market for airport slots. *Transportation Research Part B: Methodological*, 44(1):29–37.

Starkie, D. (1994). The us market in airport slots. *Journal of Transport Economics and Policy*, 28(3):325–329.

Starkie, D. (1998). Allocating airport slots: a role for the market? *Journal of Air Transport Management*, 4(2):111–116.

Swaroop, P., Zou, B., Ball, M. O., and Hansen, M. (2012). Do more US airports need slot controls? a welfare based approach to determine slot levels. *Transportation Research Part B: Methodological*, 46(9):1239–1259.

United States Government Accountability Office (2012). Slot-controlled airports - faa's rules could be improved to enhance competition and use of available capacity. Last accessed on 26 April 2022.

Zhang, A. and Czerny, A. I. (2012). Airports and airlines economics and policy: An interpretive review of recent research. *Economics of Transportation*, 1(1):15–34.

Zografos, K. G., Madas, M. A., and Androutsopoulos, K. N. (2017). Increasing airport capacity utilisation through optimum slot scheduling: review of current developments and identification of future needs. *Journal of Scheduling*, 20(1):3–24.

Zografos, K. G., Salouras, Y., and Madas, M. A. (2012). Dealing with the efficient allocation of scarce resources at congested airports. *Transportation Research Part C: Emerging Technologies*, 21(1):244–256.

Westfälische Wilhelms-Universität Münster, Institute of Transport Economics, Working Paper Series

27. **“Evaluating the Transport-Mode-Specific Trade Effects of Different Transport Infrastructure Types”**
    by Jan Wessel, February 2019

28. **“The impact of delays on the welfare effects of on-track competition: The case of transfer passengers with operator-tied tickets”**
    by Christina Brand and Gernot Sieg, December 2019

29. **“Ride-Hailing Services in Germany: Potential Impacts on Public Transport, Motorized Traffic, and Social Welfare”**
    by David Ennen and Thorsten Heilker, January 2020

30. **“Quantifying the phantom jam externality: The case of an Autobahn section in Germany”**
    by Kathrin Goldmann and Gernot Sieg, March 2020

31. **“TEN-T Corridors – Stairway to Heaven or Highway to Hell?”**
    by Kathrin Goldmann and Jan Wessel, June 2020

32. **“Using weather forecasts to forecast whether bikes are used”**
    by Jan Wessel, June 2020

33. **“Some People Feel the Rain, Others Just Get Wet: An Analysis of Regional Differences in the Effects of Weather on Cycling”**
    by Kathrin Goldmann and Jan Wessel, July 2020

34. **“The impact of the Covid-19 pandemic and government intervention on active mobility”**
    by Alessa Möllers, Sebastian Specht and Jan Wessel, April 2021

35. **“How Information on Emissions per Euro Spent can Influence Leisure Travel Decisions”**
    by Thomas Hagedorn and Jan Wessel, May 2022

36. **“Effects of the use-it-or-lose-it rule on airline strategy and climate”**
    by Till Kösters, Marlena Meier and Gernot Sieg, January 2023

For a complete list of Working Papers published by Westfälische Wilhelms-Universität Münster, Institute of Transport Economics, please visit the website (http://www.iv-muenster.de)