Do airlines adopt sustainable aviation fuels under modal competition?

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Abstract

Reducing the level of carbon dioxide (CO2) emissions in air transport calls for policies supporting less polluting fuels. The International Civil Aviation Organization and the European Union have launched policies to support the adoption of sustainable aviation fuels (SAFs). Besides this, Schiphol, Heathrow, and airports from the Swedavia AB group are already considering a system of differentiated airport charges based on environmental performance. However, the use of discriminatory charges is forbidden under Article 15 of the Chicago Convention. Our paper studies the impact of authorizing differentiated charges in the context of intermodal competition. We find that with uniform tariffs, airlines have no incentive to use SAFs. Instead, if a regulator authorizes discriminatory aeronautical charges, airlines may have the incentive to switch to a SAF and kerosene blend. When the costs associated with using a blend are smaller than passengers' disutility when not traveling with their preferred transportation mode, discriminatory charges increase air transportation's market share. Hence, using a blend may prevent losing passengers to the rail in the context of passengers' increasing environmental awareness.

Keywords— Air Transport, Regulation, Sustainable Aviation Fuels, Two-sided Platforms, Intermodal Competition.

JEL Classification – L1, L5, L93, Q55, R48

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1 Introduction

During the 41st International Civil Aviation Organization (ICAO) Assembly in 2022, 184 states and 57 organizations adopted the goal of achieving net-zero carbon (CO2) emissions in aviation by 2050.[1] Although aviation currently accounts for approximately 2% of global CO2 emissions (ICAO, 2019b), the sector's impact on climate change is projected to rise due to an anticipated annual demand growth of 4.3% over the next 20 years (ICAO, 2019a). This expected increase underscores the urgency of reducing aviation's carbon footprint. Achieving this target calls for policies that promote less CO2-intensive technologies while also leaving room for decentralized approaches, such as a system of differentiated airport charges based on the type of fuel used by airlines (EASA, 2022b). For example, airports could offer reduced take-off and landing fees or other specific fees for airlines using sustainable aviation fuels (SAFs) or adopting more radical technologies like hydrogen or electric propulsion systems.[2] Schiphol, Heathrow, and airports within the Swedavia AB group are already considering such an approach (EASA, 2022b). While Article 15 of the 1944 Chicago Convention prohibits discriminatory airport charges due to potential competition distortion[3], Article 3 of the European Union's Airport Charges Directive (ACD) allows for charge modulation in matters of public and general interest, including climate change mitigation (European Parlament and of the Council, 2009).[4]

This paper analyzes the role airports can play in the energy transition of the air transport sector if regulators allow them to set discriminatory tariffs while keeping other types of policies unchanged.[5] We show that under the current regulation, i.e., uniform charges, an airport's profit-maximizing strategy would be to serve only the most polluting airline if the adoption level of SAFs is asymmetrical. However, if a regulator allows differentiated aeronautical charges, the airport can achieve higher profits by serving both airlines. Thus, a modulation based on environmental performance can contribute to reducing emissions from air transportation.

[1]The ICAO (2019b) estimates that to achieve carbon-neutral growth, the sector will need to offset 2.5 billion metric tons of CO2 emissions between 2021 and 2035.

[2]New propulsion systems based on hydrogen or electricity represent a significant technological shift in the aviation sector

[3]The Chicago Convention lays the groundwork for international aviation; it addresses aspects such as airspace use, aircraft registration, and safety, and exempts jet fuel from taxes.

[4]For a modulation to qualify as an issue of public and general interest, it must be based on government policy. National Independent Supervisory Authorities (ISAs) assess whether the modulation aligns with Article 3, it may need to relate specifically to an element of national aviation policy. Additionally, it must comply with the ACD criteria: relevance, objectivity, and transparency (Thessaloniki Forum of Airport Charges, 2021).

[5]For instance, no carbon-related fuel tax.

Figure 1: Main characteristics of SAFs' production pathways

Production Pathway	Hydroprocessed Esters and Fatty Acids (HEFA)	Advanced Biomass to Liquids (ABtL)	Power-to-Liquids (PtL)
Kerosene type	Bio-kerosene	Bio-kerosene	E-kerosene
Feedstock	Residual oils*	Municipal waste and crops (waste)*	Hydrogen and CO2
Availability	Very constrained	Constrained	Least constrained
Strong demand from	Other transportation modes	Other transportation modes, construction, and heating	Steel and fertilizer production
Conversion Process	Hydroprocessing Cracking and isomerization	Biomass Gasification+Fischer-Tropsch Alcohol-to-Jet	Fischer-Tropsch Methanol synthesis
Emissions savings	74-84%	66-94%	89-99%
Readiness (IEA scale)	Up to 10/11 – commercially available	Up to 6/11 – proven to be deployed	Up to 5/11 - prototype
Extra Cost	0.26 EU/l	1-1.5 EU/l	1.25 EU/l

*List of advanced biofuels in Annex IX part A RED

Source: Authors' elaboration using information from ICCT (2022) and PwC (2022).

In parallel with these airport-specific initiatives, some global and regional policies have been introduced to promote less CO2-intensive technologies across the aviation sector. For instance, in 2021, the ICAO launched the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), structured in three phases, with participation being voluntary during the first two phases and becoming compulsory from 2027 onward.[6] In CORSIA, airlines can offset their CO2 emissions by using SAFs or adopting other technological improvements.[7] Additionally, the European Commission's "Fit for 55" legislative package, introduced in 2021, aims to reduce greenhouse gas (GHG) emissions by 55% by 2030 compared to 1990 levels. This package includes revisions to key policies such as the Renewable Energy Directive (RED II), the Energy Tax Directive (ETD), and the Emissions Trading System (ETS). Specifically for aviation, the ReFuelEU Aviation proposal mandates a minimum share of drop-in SAFs—advanced biofuels and e-fuels—for all flights departing from European airports.[8] Drop-in SAFs have a high potential for emissions reduction as they are fully compatible with existing aircraft and fuel infrastructure. According to Mayeres et al. (2023), the combustion emissions of fossil fuels and SAFs are similar; thus, the added value of the latter depends on how sustainable their production pathway is (Table 1). Despite the significant emissions reduction potential of SAFs, their adoption in aviation has been limited, primarily due to their high cost compared to conventional jet fuel. For instance, the ICCT (2022) estimates that the per liter cost of e-kerosene, generated by combining hydrogen and CO2, is approximately twice that of fossil kerosene. However, a carbon price of 85 EU per ton in 2030 and a carbon tax of 0.52 EU per liter on jet kerosene

[6]CORSIA includes a pilot phase (2021-2023), a first phase (2024-2026), and a second phase (2027-2035). Not all ICAO members participate in this scheme (e.g., China).
[7]Another alternative is to purchase carbon credits.
[8]This applies to European Union (EU) and non-EU airlines.

could bridge the cost gap between jet kerosene and some SAFs, according to the ICCT (2022). Additionally, the current production capacity for SAFs is insufficient to meet demand; today only about 0.05% of total aviation fuel demand in the EU could be covered by SAFs (EASA, 2022a).

The financial burdens placed on airlines by SAFs may limit their incentives to exceed mandated usage levels. These additional costs could also be passed on to passengers, potentially reducing overall air travel demand and, consequently, airports' revenues. Hence, airports have an incentive to participate in this subject. Airports generate revenues from both aeronautical activities and commercial activities, with the latter increasingly representing a substantial revenue stream.[9] It is now commonly accepted that airports are two-sided platforms where passengers and businesses interact (Flores-Fillol, Iozzi, & Valletti, 2018; Gillen, 2011; Malavolti, 2016; Malavolti & Marty, 2019). In such platforms, consumers on one side generate externalities on the other side (Armstrong, 2006; Rochet & Tirole, 2006), creating network effects that can influence pricing strategies. For example, airports might reduce aeronautical charges to attract more passengers and offset the lost revenue by increasing commercial fees.[10] To our knowledge, existing literature has not thoroughly examined how airports set tariffs when airlines transition to greener alternatives, particularly when this transition occurs asymmetrically. In scenarios where airlines adopt SAFs at different rates, airports relying on uniform aeronautical charges could inadvertently favor more polluting airlines when lowering charges to retain passengers. We show that differentiated charges can support the asymmetric adoption of SAFs in profit-maximizing airports and discuss the relevance of such strategies in the context of the ongoing energy transition. This is relevant considering the current limited SAF production capacity, as differentiated charges are intended as a short-term tool, as mentioned by Thessaloniki Forum of Airport Charges (2021).

Beyond the challenges posed by the transition to SAFs, airlines also face increasing competition from other modes of transportation, such as rail. Currently, rail travel in the EU costs roughly three times more per kilometer than air travel (OFS, 2022).[11] However, EIB (2020) suggests that growing environmental awareness among consumers might lead them to choose

[9] For instance, in 2014, about 61% of Paris Airports' revenues came from commercial activities, compared to about 54% in 2009 (Malavolti & Marty, 2019).

[10] Commercial fees include parking fees and commercial rents.

[11] This situation is reversed in China, where rail travel is more cost-effective.

trains over planes when an alternative is available. Empirical evidence shows that High-Speed Rail (HSR) can reduce demand for air travel on short- to medium-haul routes (Dobruszkes, Dehon, & Givoni, 2014; Friederiszick, Gantumur, Jayaraman, Röller, & Weinmann, 2009; Givoni, Dobruszkes, & Lugo, 2012; Wang, Jiang, & Zhang, 2021). In terms of environmental impact, D'Alfonso, Jiang, and Bracaglia (2015, 2016) show that while rail has a lower environmental footprint, the introduction of HSR may paradoxically increase CO2 emissions due to a trade-off between mode substitution and traffic generation. Despite this, intermodal competition can be beneficial by reducing ticket prices for both planes and trains (Yang & Zhang, 2012). SAFs help airlines align more closely with the environmental performance of rail, thereby intensifying the competitive pressure. To our knowledge, no theoretical models have yet explored how airlines' asymmetrical use of SAFs could impact modal competition. This paper aims to address this gap by providing a comprehensive analysis of passenger choices in an origin-destination market where consumers can choose between different transportation modes. Specifically, consumers can fly or take the train in our setup. We show that under the current regulation when both modes are seen as close substitutes the SAF-using airlines may not be able to operate in markets with modal competition, thereby favoring more polluting airlines.

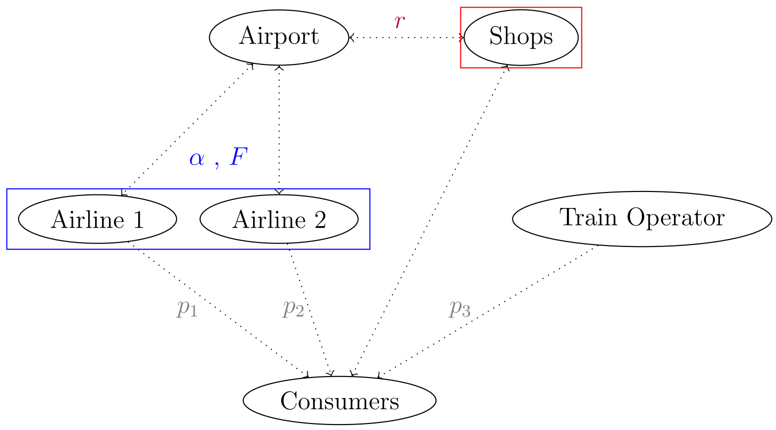
The remainder of this paper is organized as follows. Section 2 sets up the basic model. Section 3 presents the benchmark equilibrium outcome. Section 4 presents the equilibrium outcome when airlines can use a blend under different airport tariffs. Section 5 concludes the paper.

2 The Model

We consider an OD market where consumers can choose between different transportation modes, specifically, in our model, consumers can fly or take the train (Figure 2).

Our goal is to provide a global picture of passengers' choices when they can access different transportation offers. This approach will allow general policy recommendations (taxes, subsidies, and tariff designs) that consider the global supply in a given market. According to Dobruszkes et al. (2014), intermodal competition is strong in markets with less than 3 hours of rail travel. Thus, we limit our analysis to markets where the two modes of transportation coexist, i.e., where the total travel time by rail is greater than 3 hours. Furthermore, we assume

Figure 2: Organization of the market



demand is large enough to support more than one firm per mode. Three firms $k \in \{1, 2, 3\}$ serve this market: two airlines $k = \{1, 2\}$, and a train operator $k = 3$. Including two airlines allows us to assess how a regulation change could influence airlines' choices (e.g., prices and output) when facing inter- and intramodal competition. Furthermore, this latter situation corresponds to real life situations. For instance, in the Paris-Toulouse market, a full-service (Air France) and a low-cost carrier (Easyjet) compete with France's national state-owned railway (the SNCF).[12] In this market, it takes about 4h21 to reach the other city by train (the shortest route), while it takes about 1h15 by plane. Nevertheless, airports (Orly/CDG and Toulouse Airport), unlike rail stations (Montparnasse and Matabiau), are located on the outskirts of the cities. This distance evens out the final travel time between the two modes. Other examples are the Biarritz-Paris and Brussels-London markets. Air France, Transavia, and the SNCF serve the former; while British Airways, Brussels Airlines, and Eurostar operate in the latter.[13]

2.1 Supply-Side

We build on Salop (1979) and consider that the three firms are symmetrically distributed along a circle of unit length at $\frac{k-1}{3}$ (see Figure 3). Their locations aggregate a set of hedonic characteristics. Firms compete in prices for passengers.

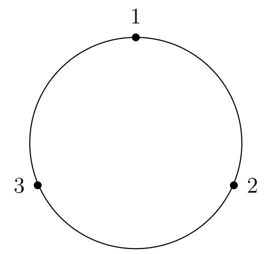
2.1.1 Rail Travel

We consider a monopolist train operator with an operational cost per passenger equal to c_T.

[12] In 2019, the SNCF introduced a low-cost rail offer between the two cities: Ouigo.

[13] Air France operates through its Air France Hop brand in the Biarritz-Paris market. This brand was created to compete with low-cost carriers. That is, its operational costs are close to those of low-cost carriers.

Figure 3: Product Space



2.1.2 Air Travel

The two airlines operate from the same monopolist airport. The latter is a two-sided platform where passengers and shops meet. Passengers buy tickets from airlines and purchase goods or services from shops.

- **Aeronautical-side**: Following Article 15 of the 1944 Chicago Convention, airlines pay the same two-part airport charge[14], which combines a per-unit fee:

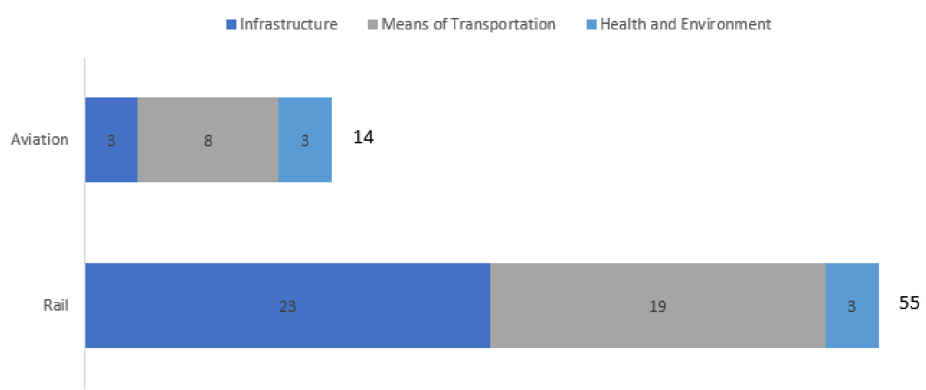
$$\alpha_1 = \alpha_2 = \alpha$$

and a fixed lump-sum fee:

$$F_1 = F_2 = F$$

In the EU, rail's costs are larger than those of air transport: $c_T - \alpha > 0$ (Figure 4).

Figure 4: Total transport cost per passenger per kilometer for the sector (CHF cents).



Source: OFS (2022)

[14] Martimort, Pommey, and Pouyet (2022) recommends the use of this type of tariffs for airport services.

We define:

$$c_k = \begin{cases} \alpha & \text{if} \quad k = 1,2 \\ c_T & \text{if} \quad k = 3 \end{cases}$$

- **Commercial-side**:

  Shops address their demand to the airport $S(D_A, r) = \gamma D_A(\alpha) - r$, it depends on the number of air passengers $D_A = D_1 + D_2$ and the rent paid by shops to the airport r.

$$\frac{\partial S(.)}{\partial D_A} > 0 \qquad \text{and} \qquad \frac{\partial S(.)}{\partial r} < 0$$

  The parameter $1 \geq \gamma \geq 0$ allows us to capture the fact that not all air passengers shop or use other paying facilities (e.g., parking or buses) at the airport. It represents the share of passengers paying for commercial activities.

The airport linear operating costs $C(D_A) = fD_A(\alpha)$ increase with the number of passengers:

$$\frac{\partial C(.)}{\partial D_A} = f > 0$$

Assumption 1. *$c_T > \alpha + f$ the operational costs per passenger of air are larger than rail travel.*

2.2 Demand-Side

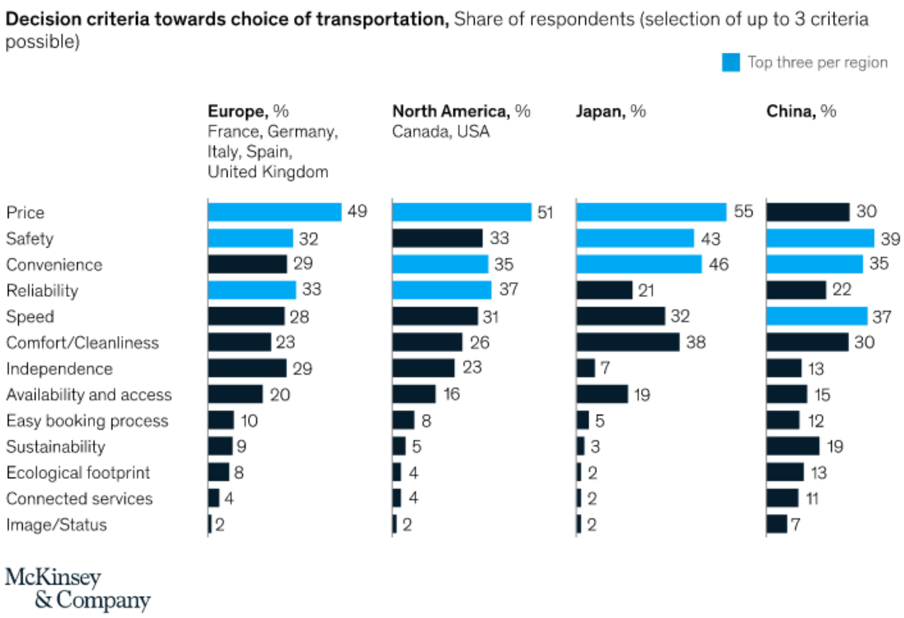
We consider a unit mass of passengers located along the circle. Each passenger's location x describes its ideal form of travel. Purchasing a ticket from a firm that offers a different trip than the passenger's preferred one results in a disutility equal to td, where $t > 0$ is a unit cost, and d is the distance in the product space between the firm's product and the passenger's preferred one. This configuration allows us to capture the fact that, beyond the price, consumers care about other features of their trip, such as travel time, frequency, and loyalty programs (see Figure 5).[15]

The net utility of a passenger located at x, traveling with a firm k is equal to:

$$U_k = \beta_k - p_k - t|\frac{k-1}{3} - x|$$

[15]For instance, Koech, Buyle, and Macário (2023) find that when consumers participate in a frequent flyer program, they tend to stick with the same airline brand even for a perceived lower quality.

Figure 5: Passengers' key criteria when selecting a transportation mode



Source: McKinsey & Company (2022)

Assumption 2. *$\beta_k > p_k$ all passengers buy one ticket.*

We assume that all the passengers buy from one firm, i.e., the market is covered.

Assumption 3. *$\beta = \beta_1 = \beta_2 = \beta_3$ passengers have the same reservation price for all firms.*

For tractability, we assume that the reservation utility is always the same in this market, but in practice, it may differ between and within travel modes. For instance, $\{\beta_1, \beta_2\} \neq \beta_3$ could be related to air travel fear, and $\beta_1 \neq \beta_2$ could be related to quality preferences (e.g., low-cost carrier versus full service).

2.3 Timing

Firms' interactions are non-cooperative and take place in three stages. The timing of the game is as follows:

- $T = 1$: The airport sets the aeronautical charges for airlines and the rent for shops.
- $T = 2$: Firms compete in prices for passengers.
- $T = 3$: Demand realises.

Our equilibrium concept is a sub-game perfect Nash equilibrium.

3 Benchmark

This section characterizes competition between and within transportation modes when airlines use jet fuel kerosene. We solve the game by backward induction (see Figure 6).

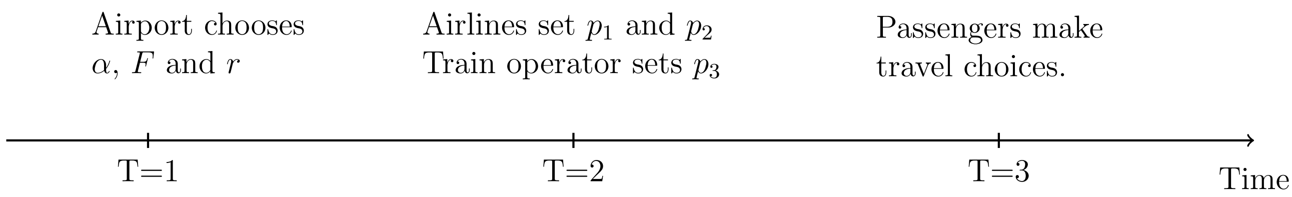


Figure 6: Decision Timeline

In stage 3, passengers buy tickets at the prices chosen by the firms. We determine the demand functions for each firm. Let $x_{k,k+1}$ be the passenger indifferent between travelling with firm k and firm $k+1$:

$$U_k - t|\frac{k-1}{3} - x_{k,k+1}| = U_{k+1} - t|\frac{k}{3} - x_{k,k+1}|$$

thus, demand for firm k writes:

$$D_k = \begin{cases} \frac{p_2+p_3-2p_1}{2t} + \frac{1}{3} & \text{if} \quad k = 1 \\ \frac{p_1+p_3-2p_2}{2t} + \frac{1}{3} & \text{if} \quad k = 2 \\ \frac{p_1+p_2-2p_3}{2t} + \frac{1}{3} & \text{if} \quad k = 3 \end{cases}$$

In stage 2, the three firms compete in prices. Firms' k program writes:

$$\underset{\{p_k\}}{Max} \quad \pi_K = D_k(p_k - c_k) - F\mathbb{1}_{k=\{1,2\}}$$

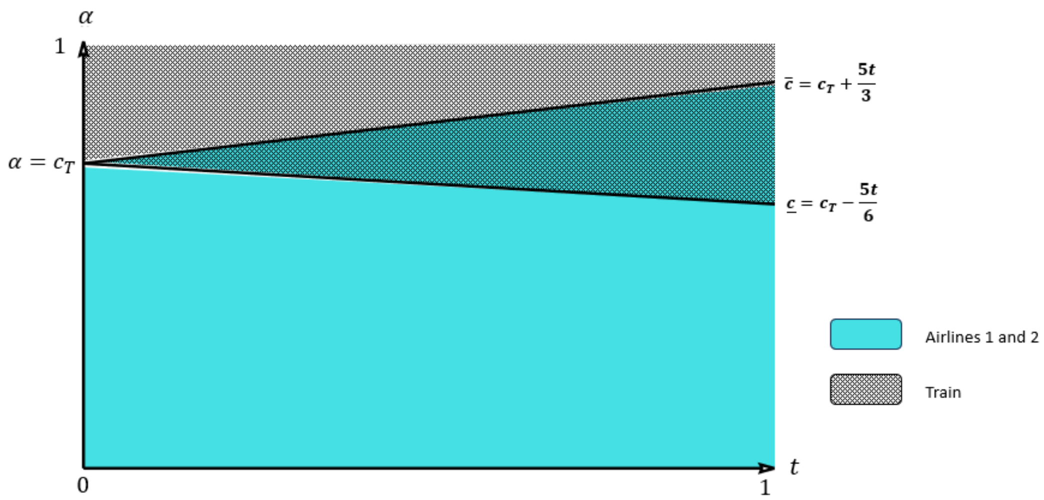
Lemma 1. *When $\bar{c} = c_T + \frac{5t}{3} > \alpha > \underline{c} = c_T - \frac{5t}{6}$ both airlines and the train operator are active in the market. Hence, passengers have the choice between traveling by air or rail. Otherwise, when $\alpha \leq \underline{c}$ (respectively. $\bar{c} \leq \alpha$) only air (respectively. rail) travel is available for passengers.*

Proof. See Appendix A.1. □

Today rail's operational costs are about three times larger than air $\bar{c} > c_T > \alpha > 0$.[16]

[16] The OFS (2022) estimates a cost per passenger per kilometer at 0.46 CHF for rail and 0.13 for air transport.

Figure 7: Firms active in the market



The two modes of transportation co-exist in markets where the cost difference between them is strictly smaller than passengers' disutility associated with not traveling by their preferred transportation mode: $t > \frac{5t}{6} > c_T - \alpha$ (Figure 7). Otherwise, when $\frac{5t}{6} \leq c_T - \alpha$ passengers can only travel by plane. However, air travel's operational costs could increase because of the new policies to reduce the carbon footprint of the sector. For instance, with the revised ETD jet fuel will no longer be exempt from taxes. Also, airlines' freely allocated emissions quotas in the EU-ETS will end in 2027. The main cost driver for HSR is the electricity price which depends on the energy mix of the region of interest. Thus, it might decrease or increase in the future.

In stage 1, the airport sets the aeronautical charges for airlines and the rent for shops. The airport's program writes:

$$\underset{\{\alpha,r,F\}}{Max} \quad \pi_A = D_A(\alpha)(\alpha - f) + 2F + rS(D_A(\alpha), r)$$

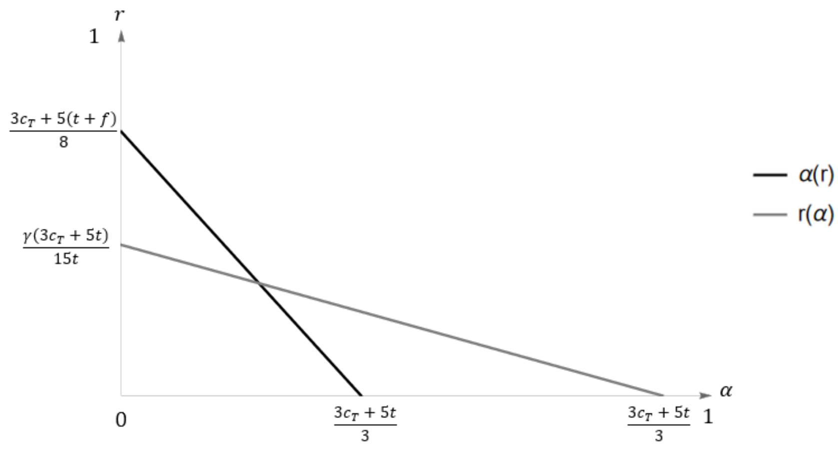
with $D_A(\alpha) = D_1(\alpha) + D_2(\alpha) = \frac{2(c_T-\alpha)}{5t} + \frac{2t}{3}$ the demand addressed to the airport. Airlines operate from this airport if the lump-sump fee is such that $D_k(\alpha)(p_k - \alpha) \geq F$. This implies that the lump-sum fee set by the airport must satisfy the following participation constraints (PC), respectively, for airlines 1 and 2:

$$D_1(\alpha)(p_1(\alpha) - \alpha) \geq F \qquad \text{(PC1)}$$

$$D_2(\alpha)(p_2(\alpha) - \alpha) \geq F \qquad \text{(PC2)}$$

Notice that strategically using the lump-sum fee to extract all the airline's profits is only possible in the context of a monopolist airport.

Figure 8: Aeronautical charges and rent cross-externalities



The larger the share of passengers paying for commercial activities at the airport, the smaller (respectively. larger) the per unit aeronautical charge (respectively. rent) set by the airport. When the airport considers the externalities between the two sides of the platform, given that $c_T > f$, an increase in the proportion of passengers shopping at the airport results in a lower per-unit aeronautical charge. The airport uses this discount to attract passengers and compensates for this reduced fee with a higher rent and lump-sum fee (Figure 8).

Lemma 2. *The demand addressed to the airport is positive when passengers' disutility from not traveling with their preferred means of transportation is large compared to the share of passengers consuming at the airport: $t > \hat{t} = \frac{\gamma^2}{8}$. Otherwise, passengers travel only by train.*

Proof. See Appendix A.2. □

Notice that the lump-sum fee set by the airport always increases with rail's operational cost: $\frac{\partial F}{\partial c_T} = \frac{2t(3(c_t - f) + 5t)}{3(8t - \gamma^2)^2}$. This is also true for the rent set by the airport as long as $t > \hat{t}$. Regarding the per-unit airport charge, the latter may decrease with rail's operational cost if the passengers' disutility from not traveling with their preferred means of transportation is not large enough. That is when $\hat{t} < t < \frac{\gamma^2}{3}$. Else, if passengers' disutility is such that $t > \frac{\gamma^2}{3} > \hat{t}$, then competition from the other mode increases both the aeronautical charges and the rent set by the airport. When passengers strongly dislike buying from other firms, the airport can exert market power on both sides of the platform. Otherwise, it prefers to reduce the per-unit airport charge at the expense of rent and the lump-sum fee.

4 Sustainable Aviation Fuel

We now assume that airline $k = 2$ can operate using a drop-in SAF and kerosene blend.[17] This strategy allows airline 2 to simultaneously reduce its CO2 emissions level and differentiate its product further from airline 1's. In terms of the game's timing, this adds a preliminary stage ($T = 0$) in which airline 2 decides whether or not to blend kerosene with drop-in SAFs. This strategy raises airline 2's operational costs from α to $\delta c_{SAF} + \alpha$. According to the ICCT (2022), the cost difference between fossil kerosene and e-kerosene is 1.5 EU per liter. Here δ represents the percentage of drop-in SAFs that can be safely blended with jet fuel kerosene.[18] We consider that the airline using the blend moves closer to the train operator's product (Hoernig, 2015). As a result, firms are no longer symmetrically located along the circle: airline 2 is at a distance $\frac{1}{3} - \delta$ from the train operator and distance $\frac{1}{3} + \delta$ from airline 1.

Assumption 4. $\frac{1}{3} \geq \delta > 0$.

We assume that airline 1's and the train operator's locations remain unchanged along the circle. Indeed, even though they may want to change their strategies, i.e., their position in the circle, this may not be possible in the short term.[19] Airline 2 becomes a closer substitute to rail travel and we have more differentiated airlines in the market (see Figure 9). The larger the percentage of SAFs used by airline 2, the closer its environmental performance will be to the one of firm 3, i.e., to rail.

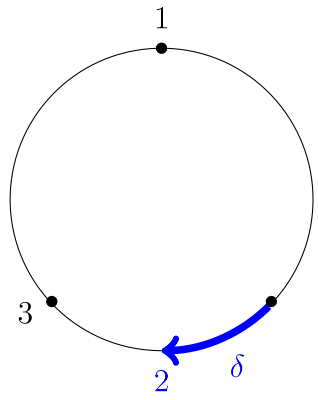
Furthermore, we assume that the size of the market remains unchanged. Despite some consumers valuing environmental quality, SAFs are more expensive than fossil kerosene, making market expansion difficult. According to PwC (2022), the use of SAFs could increase the final air ticket price by about 9-16%.

[17]This could also reflect a situation where airline 2 chooses to use for SAF than mandated in the EU, while airline 1 only uses the mandated level.

[18]Today, depending on the SAF production pathway, this percentage ranges between 10% and 50%. Nine production pathways have been approved by EASA as of 2023: seven for bio and two for e-kerosene.

[19]For instance, changing the firm's departure time could conflict with other train lines or flights.

Figure 9: Product Space



4.1 Uniform aeronautical charges

First, we consider that regulation stays as in our benchmark case, i.e., the airport cannot charge differentiated fees to airlines. Again, we solve the game by backward induction. In stage 3, passengers buy tickets at the prices chosen by the firms. We follow Hoernig (2015) and determine the consumer $x_{k,k+1}$ indifferent between buying from firm k and firm $k+1$:

$$x_{k,k+1} = \frac{1}{6} + \frac{\delta_k - \delta_{k+1}}{2} + \frac{p_{k+1} - p_k}{2t}$$

the demands for each firm are:

$$D_k = \begin{cases} \frac{p_2+p_3-2p_1+t\delta}{2t} + \frac{1}{3} & \text{if} \quad k=1 \\ \frac{p_1+p_3-2p_2}{2t} + \frac{1}{3} & \text{if} \quad k=2 \\ \frac{p_1+p_2-2p_3-t\delta}{2t} + \frac{1}{3} & \text{if} \quad k=3 \end{cases}$$

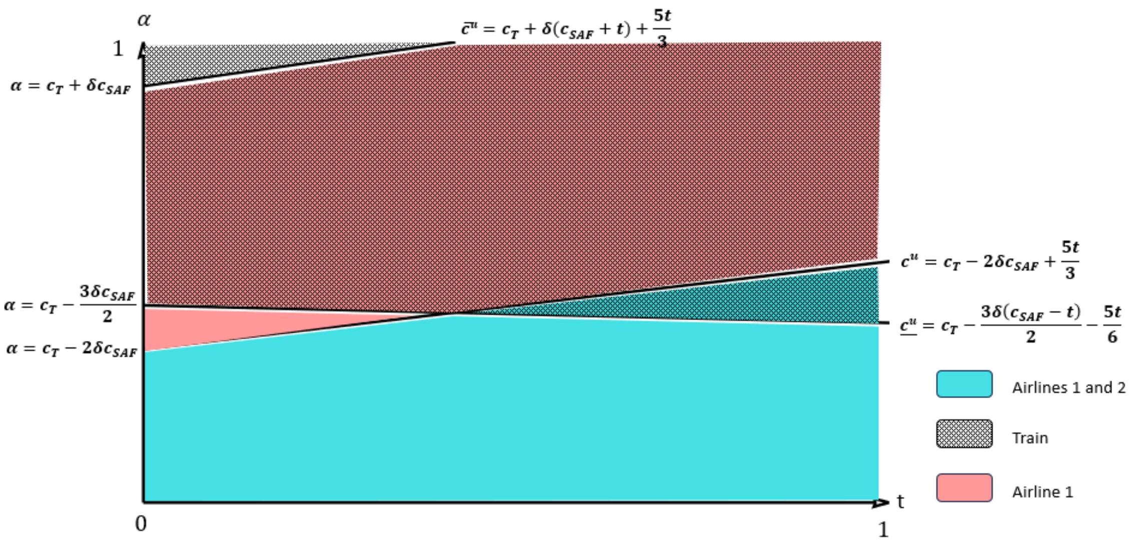
In stage 2, the three firms compete in prices. Firms' k program writes:

$$\underset{\{p_k\}}{Max} \quad \pi_K = D_k(p_k - c_k) - F\mathbb{1}_{k=\{1,2\}}$$

Lemma 3. *When $\bar{c}^u = c_T + \delta(c_{SAF} + t) + \frac{5t}{3} > \alpha > c_T - \frac{3\delta(c_{SAF}-t)}{2} - \frac{5t}{6} = \underline{c}^u$ both airlines and the train operator are active in the market. Hence, passengers have the choice between traveling by air or rail. Otherwise, when $\alpha \leq \underline{c}^u$ (respectively. $\bar{c}^u \leq \alpha$) only air (respectively. rail) is available for passengers. Notice that when $\bar{c}^u > \alpha > c_T - 2\delta c_{SAF} + \frac{5t}{3}$ only the less environmentally friendly airline operates.*

Proof. See Appendix A.3. □

Figure 10: Firms active in the market



When airline 2 uses a blend, the threshold value of the air operational costs at which consumers can no longer fly is higher than in the benchmark ($\bar{c} < \bar{c}^u$). Thus, airline 1 continues to compete with rail even when the per-unit fee α is very high such that airline 2 can no longer operate in the market ($c^u < \bar{c} < \bar{c}^u$). Indeed, in such a case, airline 2 would make negative profits if it stayed in the market. This is the result of airlines becoming more differentiated and airline 2 having larger operational costs compared to the benchmark. In terms of environmental impact, we have two opposing effects. On the one hand, airline 2's level of emissions decreases. On the other hand, airline 1 operates more, which increases its emissions. Airline 1's demand is higher than in the benchmark case, whereas airline 2's is lower. Depending on the magnitude of the additional costs associated with using a blend δc_{SAF}, compared to the passenger's disutility associated with not traveling with their preferred transportation mode $t(5 - 3\delta)$, airline 2 may never compete with rail (Figure 10). That is when $\delta c_{SAF} > t(5 - 3\delta)$, i.e. when the operational costs of airline 1 are such that $\alpha < c^u < \underline{c}^u$. Thus, depending on the size of the extra costs from using a blend, airline 2 may only be able to operate in markets without inter-modal competition. This raises concerns about the lack of incentives to use an environmentally friendly fuel when other airlines in the same market stay with fossil kerosene. If it is too costly to use the blend we may never observe asymmetrical adoption of SAFs.

In stage 1, the airport sets the aeronautical charges for airlines and the rent for shops. The airport's program writes:

$$\underset{\{\alpha,r,F\}}{Max \quad \pi_A} = D_A(\alpha)(\alpha - f) + 2F + rS(D_A(\alpha), r)$$

$$\text{s.t.} \quad D_1(\alpha)(p_1 - \alpha) \geq F \qquad \text{(PC1)}$$

$$D_2(\alpha)(p_2 - \alpha - \delta c_{SAF}) \geq F \qquad \text{(PC2)}$$

with the demand addressed to the airport equal to $D_1(\alpha) + D_2(\alpha) = \frac{2(c_T-\alpha)-\delta(c_{SAF}-t)}{5t} + \frac{2}{3}$. Again airlines only operate from the airport when the lump-sum fee is smaller than the gross profits. Nevertheless, now the participation constraints differ for airlines 1 and 2.

- Airline 1 is active if:

$$\frac{(3(c_T - \alpha + \delta t) + 5t)^2}{225t} \geq F$$

- Airline 2 is active if:

$$\frac{(3(c_T - \alpha) + 5t)^2}{225t} \geq F$$

According to Article 15 of the 1944 Chicago Convention, the airport cannot use discriminatory aeronautical charges. Thus, we have different cases depending on who the airport chooses to serve and the cost difference between transportation modes. The airport has the choice between setting a lump-sum price equal to the gross profit of the airline with the highest gross profit $F = max\{\pi_1 + F, \pi_2 + F\}$ and excluding the other airline from the market or setting the lump-sum fee at the lowest gross profit $F = min\{\pi_1+F, \pi_2+F\}$ and serving both airlines. That is the airport has the choice between a high lump-sum fee such that only one of the airlines can operate in the market without making negative profits or a low lump-sum fee such that both airlines make positive profits. As long as $\delta > 0$, airline 1's profits are greater than airline 2. Thus, the airport has the choice between serving only airline 1 with a lump-sum fee equal to the latter's gross profit (Case 1) or both airlines with a lump-sum fee equal to airline 2's gross profit (Case 2). Notice that depending on who the airport chooses to serve, the airline's payoffs differ (Table 1):

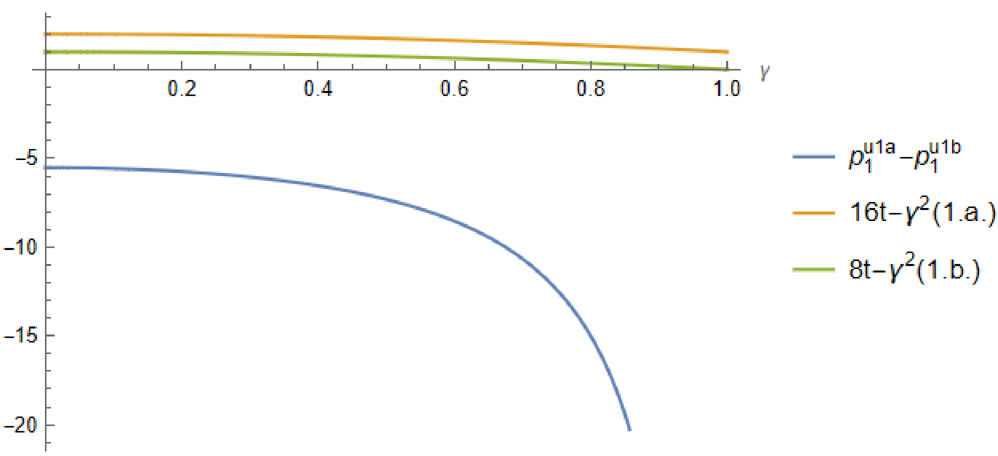
Table 1: Airlines' payoffs under uniform tariffs

Case	1	2
Airline 1	$\pi_1 = 0$	$\pi_1 > 0$
Airline 2	$\pi_2 < 0$	$\pi_2 = 0$

To determine the airport's equilibrium strategy, we compare the payoffs of the different cases. Depending on which strategy provides the highest profits, the airport may prefer to set a high lump-sum fee so that airline 2 operates at a loss. In that case, airline 2 will no longer operate in this market, i.e., it will be excluded, and the percentage of blended drop-in SAF will be null $\delta = 0$.

In case 1, when the airport only serves the airline with the highest gross profits, there are two possibilities regarding airline 2's residual demand. Passengers may choose not to travel at all, leaving the market uncovered (Case 1.a.), or they may shift toward one of the two operating firms, i.e., airline 1 or the train (Case 2.a.). Notice that when the airport serves only airline 1, regardless of having a covered or uncovered market, airline 1's profits are always null. Indeed, the structure of the aeronautical charges is such that the airport always recovers all revenues. Nonetheless, as long as $8t > \gamma^2$, airline 1's margins are higher when the market is covered (see Figure 11).

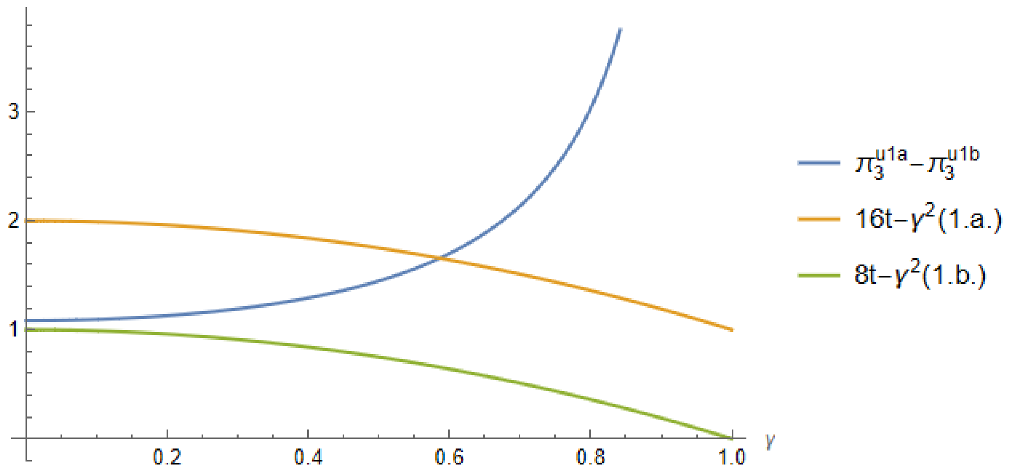
Figure 11: Airline 1's equilibrium prices case 1.a. and 1.b.



In what concerns the train operator, conversely, its profits are larger when the market is uncovered as long as the condition $8t > \gamma^2$ is met (see Figure 12). Compared to the benchmark, the train's demand is larger when airline 2 is excluded from the market ($D_3^{u1a} > D_3^*$), but its equilibrium price is smaller ($p_3^{u1a} < p_3^*$). This is the result of a larger competitive pressure.

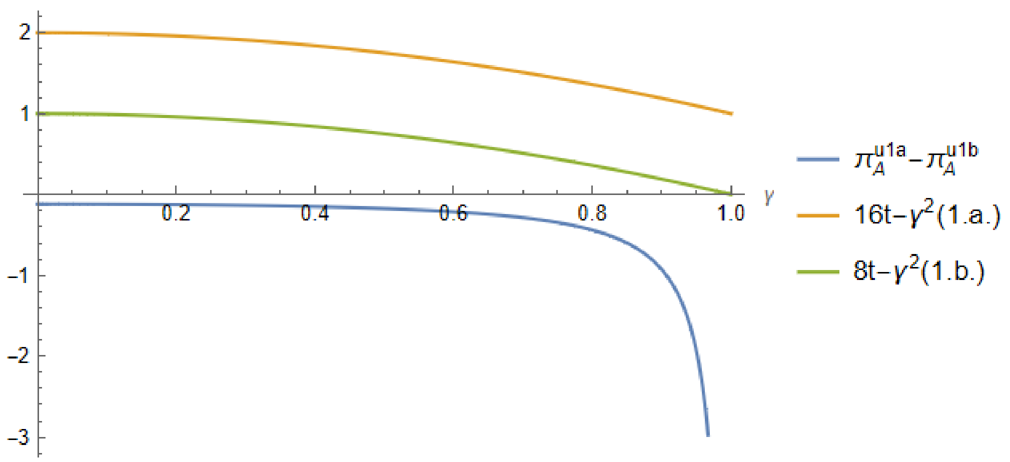
Indeed, now the firms have the same competitor on both sides of the circle.

Figure 12: Train operator equilibrium profits cases 1.a. and 1.b.



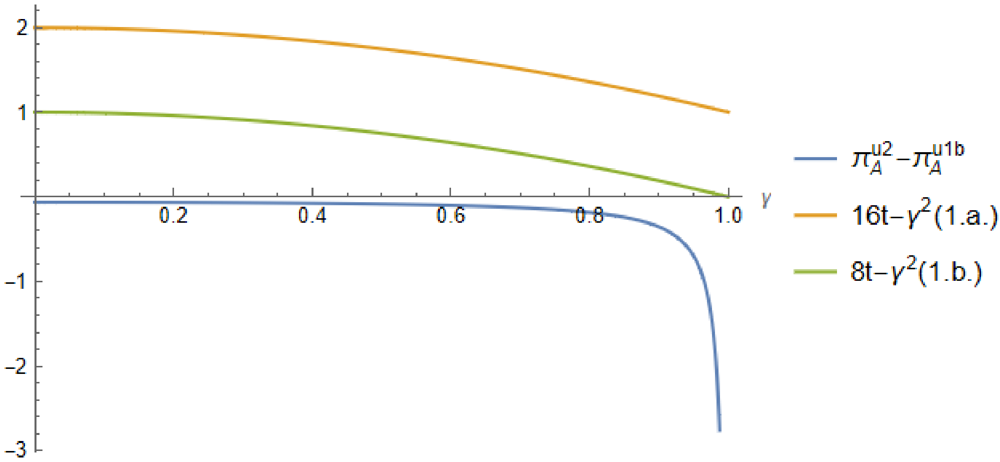
The airport always prefers to have a covered market when the condition $8t > \gamma^2$ is met (see Figure 13). Assumption 1 implies that the reservation price in this market is high enough for all passengers to always buy one ticket. So when airline 2 is excluded from the market, passengers shift to other transportation modes, and the market remains covered. In practice, whether the market remains covered or not depends on how many passengers no longer travel when their preferred transportation mode is no longer available. For instance, if we consider passengers going to a conference without an online participation option, they will either switch to airline 1 or take the train.

Figure 13: Airport equilibrium profits cases 1.a. and 1.b.



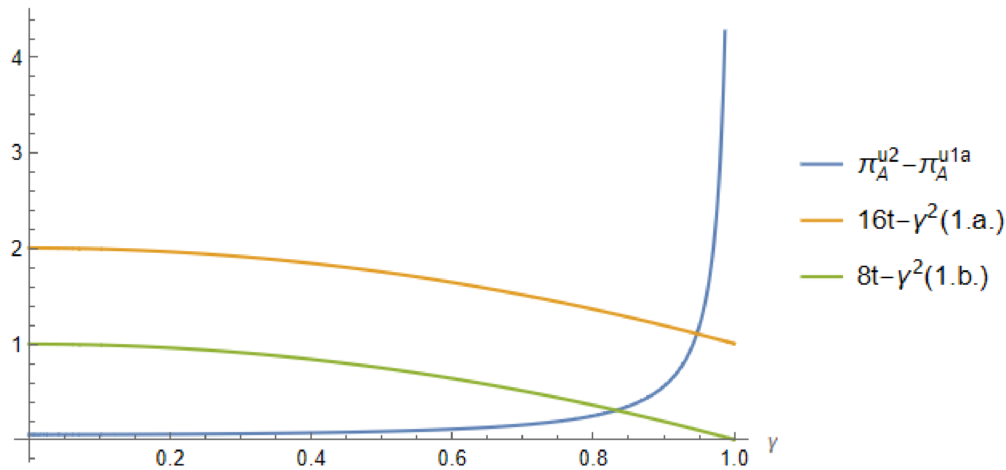
Provided that we have always a covered market, as long as the condition $8t > \gamma^2$ is met, then the airport prefers to serve only airline 1 rather than serving both airlines when one of them chooses to use a SAFs and jet fuel kerosene blend (see Figure 14).

Figure 14: Airport equilibrium profits cases 2 and 1.b.



Conversely, if market coverage cannot be guaranteed, (i.e., passengers can stop traveling) provided that the condition $8t > \gamma^2$ is met, then the airport profits are larger when the airport serves both airlines compared to the case when it only serves airline 1 (see Figure 15). In practice, it is quite difficult to imagine that all the passengers who used to travel with airline 2 will stop traveling. Especially because when the market is covered, the train's equilibrium prices are lower and therefore more accessible to passengers (i.e., smaller) as a result of the more intense competitive pressure.

Figure 15: Airport equilibrium profits cases 2 and 1.a.



Proposition 1. *If passengers have a sufficiently high reservation value, such that the market is always covered, then the airport always prefers to exclude the airline using a blend from the market, provided that passengers' disutility from not traveling with their preferred means of transportation is large compared to the share of passengers consuming at the airport ($t > \hat{t}$).*

Proof. When the passengers' reservation price is such that the market is always covered, the total demand addressed to the airport is larger when airline 2 does not operate in the market: $D_A^{u1b} > D_A^{u2}$ as $-33\delta c_{SAF} < t(10-9\delta)$ (recall that $\delta \in [0; \frac{1}{3}]$). Moreover, by setting a lump-sum fee such that airline 2 no longer operates in this market, the airport reduces the inter-modal competitive pressure, which allows airline 1 to increase its margins. The lump-sum fee is such that the airport fully extracts airline's 1 gross profits, which are larger when the airport serves only airline 1. Thus, as long as the demand addressed to the airport is always positive, when $t > \hat{t}$, the airport prefers to serve only airline 1. For the detailed computations, see Appendix A.4. □

Recall from Lemma 3 that a necessary condition for a positive demand addressed to the airport is that the disutility of not traveling with the preferred means of travel needs to be large enough $t > \hat{t}$. Otherwise, passengers will only travel by train. In a market where two modes of transportation co-exist and passengers always travel, if one of the airlines chooses to use a blend and the airport cannot discriminate, then the former would be excluded from the market. Thus, under this market configuration at equilibrium, we never observe the unilateral adoption of more environmentally friendly jet fuel. Thus, the current regulation limits airlines' incentives to reduce their CO2 emissions. If airline 2 anticipates this outcome, it will never choose to use a blend, and the equilibrium will correspond to the benchmark.

4.2 Differentiated aeronautical charges

Second, we consider that the regulator authorizes differentiated aeronautical charges. Today, Schiphol, Heathrow, and airports from the Swedavia AB group are studying the possibility of modulating aeronautical charges based on the type of fuel used by aircraft (EASA, 2022b). For instance, Schipol is studying the possibility of offering airlines that use SAFs a monetary incentive of 500 EU per ton of biofuels and up to 1000 EU per ton for e-fuels. Heathrow proposes to cover 50% of the extra costs related to the use of SAFs. In the case of airports in the Swedavia group, besides covering 50% of the extra costs related to the use of SAFs, airlines may also benefit from reduced take-off and landing charges. Airports intend to levy funds to finance these different incentives through pollution-related charges (see Figure 16). Notice that, since 2012, CO2 emissions from intra-European Economic Area (EEA) flights have been included in the EU Emissions Trading System (EU-ETS). The emission allowances allocated to airlines follow grandfathering rules: 85% are free of charge, and 15% are auctioned (European Commission, 2017). Nonetheless, airlines' freely allocated emissions quotas in the EU-ETS are expected to end by 2027.

Figure 16: Airport's proposals

Source: EASA (2022b)

Again, we solve the game by backward induction. In stage 3, passengers buy tickets at the prices chosen by the different firms. The demand addressed to each firm remains unchanged with respect to section 4.1. In stage 2, the three firms compete in prices. Firms' k program writes:

$$\underset{\{p_k\}}{Max} \quad \pi_K = D_k(p_k - c_k) - F\mathbb{1}_{k=\{1,2\}}$$

Lemma 4. *Differentiated aeronautical charges allow the airport to offer a discounted per-unit fee to the airline using the blend, such that both airlines always serve the market.*

Proof. See Appendix A.5. □

Differentiated aeronautical charges based on environmental performance allow airline 2 to benefit from a reduced per-unit fee. This discounted fee is related to the fact that when airline 2 uses a blend (see Figure 5) airline 1 faces a larger demand. The intuition is that this situation incites the airport to set a larger per-unit fee for the airline transporting more passengers (airline 1) as it allows it to generate larger revenues.

In stage 1, the airport sets the aeronautical charges for airlines and the rent for shops. The airport's program writes:

$$\underset{\{\alpha_1,\alpha_2,r,F_1,F_2\}}{Max} \quad \pi_A = D_1(\alpha_1,\alpha_2)(p_1(\alpha_1,\alpha_2)-f)+D_2(\alpha_1,\alpha_2)(p_2(\alpha_1,\alpha_2)-f)$$

$$+F_1+F_2+rS(D_A(\alpha_1,\alpha_2),r) \qquad (2)$$

$$\text{s.t.} \quad D_1(\alpha_1,\alpha_2)(p_1(\alpha_1,\alpha_2)-\alpha_1)\geq F_1 \qquad \text{(PC1)}$$

$$D_2(\alpha_1,\alpha_))(p_2(\alpha_1,\alpha_2)-\alpha_2-\delta c_{SAF})\geq F_2 \qquad \text{(PC2)}$$

Here, despite airline 2's reduced aeronautical charges, i.e., per-unit fee and lump-sum, the latter makes null profits at equilibrium. Indeed, the structure of the aeronautical charges is such that the monopolist airport extracts all the airline's profits.

Proposition 2. *There exists a tariff structure such that airline 2 can be given incentives to use a blend (indifference condition).*

Proof. Here, airlines make zero profits (as in the benchmark) as the lump-sum fees F_1^D and F_2^D allow the airport to extract all the airlines' gross profits. There is no stable equilibrium but unlike with uniform tariffs, airline 2 is no longer excluded from the market. Thus, differentiated tariffs allow a positive discrimination, i.e., to charge a lower fee to airline 2 such that it stays in the market. For the detailed computations, see Appendix A.6. □

Unlike the current regulation, modulation of airport charges allows positive discrimination, i.e., charging a lower fee to airline 2 such that it stays in the market. Thus, a decentralized approach supporting the adoption of SAFs could help to reduce emissions from air transport. In what concerns modal competition, when airline 2 uses a blend $\delta > 0$, the market share of air transportation may be lower than in the benchmark case depending on the magnitude of the additional costs associated with using a blend c_{SAF} compared to passenger's disutility associated with not traveling with their preferred transportation mode t. Indeed, if the extra costs are strictly smaller than the disutility $c_{SAF} < t$, then using a SAF and kerosene blend is a good strategy for air transport to avoid losing passengers to the rail in the context of passengers' increasing environmental concern. The blend increases the total number of passengers visiting the airport.

In this context, one may wonder what would be the outcome if the actors were able to reposition themselves in the circle. That is adapt the product they offer following the adoption of SAFs by airline 2. From Salop (1979), we know that when more than one firm horizontally differentiated firms compete in prices, at equilibrium firms locate themselves as far from each as possible. In such a case, the firms will again be located symmetrically on the circle (like in the benchmark). However, now airline's 2 operating costs are higher than in the benchmark, leading to lower gross profits. Thus, if the airport cannot discriminate, the latter would have the incentive to set an airport charge such that the SAF-using airline makes negative profits if it stays in the market.

5 Policy Implications

Airport charges in line with Article 15 of the 1944 Chicago Convention do not provide incentives for the unilateral adoption of a SAF and kerosene blend in high-value markets.[20] Specifically, if one of the airlines decides to use a blend, the airport retrieves larger profits if the lump-sum fee is such that the blend-using airline makes negative profits. Thus, the latter airline will prefer to no longer operate in that market. In such a case, the other airline not only recovers some of the exiting airline's passengers but also its margins increase as intra-modal competition is relaxed. This is beneficial for the airport as it recovers larger profits than in the benchmark case. Given that the unilateral adoption of a blend is not possible, one may wonder about the possible policy measures that could be put in place to incite airlines to use the blend. As part of the Fit for 55 legislative package, the ReFuelEU Aviation Directive mandates the use of a minimum share of drop-in SAFs for all flights departing from European airports (Figure 17).

This measure applies to EU and non-EU airlines. Thus, in theory, the EU's SAF mandate could force all airlines to adopt SAFs for flights departing European airports under the current uniform airport charges. However, today SAFs' production level is quite limited: production at the EU level could only cover about 0.05% of the total EU aviation fuel demand (EASA, 2022a).

[20]Markets for which consumers have a high reservation price.

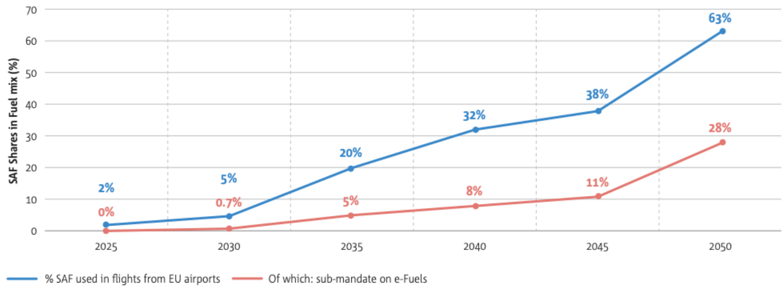


Figure 17: Fit for 55 SAF targets

Although production capacity is expected to increase in the years to come, SAFs production will still be limited by feedstock availability. This is the case for all production pathways as they face competition from other sectors and transport modes. For instance, the HEFA production pathway which today is the most advanced one relies on resources used to produce biofuels (bioethanol) for road transportation. The ABtL exploits resources that can be used to produce biomethane a low-carbon alternative to natural gas for heating. According to PwC (2022), the most promising production pathway is PtL but its ramp-up will have a slow start with global production capacity reaching only about 1 million tons per year at the 2030 Horizon. Thus, not all the airlines may be able to operate with the minimum mandated share of SAFs nor go beyond the mandated level at least in the short to medium term. This raises many questions, especially since it is difficult to imagine that airlines will simply stop operating. Could a penalty be applied to the airlines that are not able to operate with the minimum mandated SAF shared? Who will set the penalty level? Could this create incentives for airlines to wait longer for adopting SAFs? Another important point is the fact that SAFs are more costly than fossil kerosene. These additional costs will be borne by airports and airlines and are likely to be passed on to passengers. Depending on the airline's business model this could represent an average price increase of 9-16% per ticket (PwC, 2022). This cost gap between fossil kerosene and SAFs may prevail despite additional policy instruments included in the Fit for 55 package. For instance, a carbon price of 85 euros per ton in 2030 and a carbon tax of 0.52 euros per liter on jet kerosene could close the cost gap between jet kerosene and biokerosene from HEFA, according to the ICCT (2022). However, with such measures, e-kerosene would still not be cost-competitive. Thus, carbon pricing must be sufficiently high to even out the production costs of non-SAF and SAF-using airlines while considering the different possible production pathways for SAFs. Else, in high value-markets, a monopolist airport will always have the incentive to set a lump sum such that the SAF-using airline has no incentive to operate in the market. That is if it operates its profits will be negative. Furthermore, the air transport sector value chain is highly concentrated thus policy instruments such as emission permits or taxes for jet fuel will likely result in higher prices for passengers because of the double marginalization. Without a global approach to tackle aviation emissions, the above-presented measures could deeply hurt EU aviation. Indeed, as costs are likely to pass on to passengers, European airports and airlines would be less competitive compared to extra-EU. For instance, EU hubs could lose connecting passengers, who will choose to travel through non-EU airports instead. ICAO's CORSIA scheme is the first step to leveling out the playing field for EU and non-EU airlines. However, not only participation in CORSIA is "voluntary" (at least until 2027) but also some ICAO members do not participate in this scheme (e.g., China). Another concerning point is the fact that airlines can offset their CO2 emissions in CORSIA by purchasing carbon credits. The net contribution of carbon credits in terms of CO2 emissions reduction is very difficult to assess and may lead to double counting. Furthermore, their prices can be rather low compared to the social cost of carbon. Authorizing decentralized measures such as the modulation of airport charges allows positive discrimination. That is the tariffication is such that a blend-using airline can continue to operate in the market even if its rival stays with the incumbent technology. We showed that with the modulation we can maintain a high level of competition with the three firms serving the market. Thus, passengers are better off compared to the no-modulation scenario in which the blend-using airline exited the market. Even though we do not carry out a complete welfare analysis, notice that here passengers have access to more products, and thus the supply-side matches better their preferences. It is important to highlight that here the airport does not act as a regulator, but instead, it is simply authorized to set different tariffs depending on the type of fuel used by airlines. Setting different tariffs is in line with its profit-maximizing strategy. Today, such modulation is studied by Schiphol, Heathrow, and airports from the Swedavia (EASA, 2022b). However, the proposed modulation highly differs between airports. Schipol proposes to offer a per unit subsidy of 500 EU per ton of biofuels and up to 1000 EU per ton for e-fuels. Heathrow and the airports of the Swedavia group propose to cover 50% of the extra costs related to the use of SAFs. Besides in the airports from the Swedavia group, airlines may also benefit from reduced take-off and landing charges. All these airports intend to levy the funds to finance these incentives through pollution-related charges. Notice that emission charges already exist in many airports. Given the variety of airport charges and types of modulations proposed, if a regulator does authorize the use of differentiated charges it will be important to it define the proper way to do the modulation. That is, to fix the playing rules such that we can simultaneously have positive discrimination and avoid as much as possible distorting competition in a highly concentrated market.

6 Conclusion

This paper studies the incentives to use a sustainable aviation fuel (SAF) and kerosene blend in the context of intermodal competition. More broadly, we contribute to the analysis of decarbonization strategies for air transport. Air transport accounts for 2% of global carbon dioxide (CO2) emissions (ICAO, 2019b). The sector's net contribution to climate change is expected to increase with demand. This calls for policies supporting less CO2-intensive technologies but also leaves room for decentralized approaches. The ICAO as well as the EU have launched policies to support the adoption of SAFs. For instance, ReFuelEU Aviation introduces a minimum share of drop-in SAFs for all flights departing from European airports.

Other actors in the supply chain can also incite airlines to switch to SAFs. For instance, Schiphol, Heathrow, and airports from the Swedavia AB group are considering implementing a system of differentiated airport charges based on environmental performance (EASA, 2022b). However, the use of discriminatory charges is forbidden under Article 15 of the Chicago Convention. This paper has studied the incentives to authorize such differentiated charges in the context of decarbonizing air transport. Our model accounts for intermodal competition with rail. The empirical literature provides evidence that rail decreases demand for air travel and modifies the way airlines operate.[21] Our paper formalizes intermodal competition when airlines use SAFs as a strategy to compete with rail.

With uniform aeronautical charges, when the reservation price is such that passengers always travel, if one of the airlines uses a blend, then the airport would prefer to set a high lump-sum fee such that the blend-using airline no longer operates in the market. This limits airlines' incentives to reduce their CO2 emissions. Indeed, no airline will be willing to use a blend if they

[21] For instance, airlines may cover more fringe markets (Jiang & Zhang, 2016).

anticipate market exclusion. Airlines are better off when the rival airline uses a blend and they do not. Indeed, this allows them to increase their market share. Furthermore, we find that, with intermodal competition, the airport tends to increase the aeronautical and commercial charges with the cost of the other mode. This is the case when passengers strongly dislike buying other tickets than their preferred one: the airport can exert market power on both sides of the platform. Otherwise, the airport reduces the per-unit airport charge at the expense of rent and the lump-sum fee.

If a regulator authorized discriminatory aeronautical charges, then airlines would be indifferent between using a less polluting SAF and kerosene blend or not. Indeed, despite lower aeronautical charges with the blend, airlines make zero profits. This is related to the fact that the airport is always able to exert market power as it fully extracts the airlines' revenues. Unlike the current regulation, modulation of airport charges allows positive discrimination, it allows the blend-using airline to stay in the market. Thus, a decentralized approach supporting the adoption of SAFs could contribute to reducing emissions from air transport. In our model, we do not conduct a welfare analysis as it would require specifying the objective of the regulator. We abstract from whether it is socially desirable for airlines to switch to SAFs. Instead, we focus on whether a change in regulation could facilitate the adoption of less polluting fuels. Namely, whether it would be in line with the airport's profit-maximizing strategy. Notice that, with differentiated charges, the market share of air transportation can be higher than in the benchmark. This is the case when the additional costs associated with using a blend are strictly smaller than the passenger's disutility associated with not traveling with their preferred transportation mode. In such a case, using a blend is a good strategy for airlines to avoid losing passengers to rail in the context of increasing environmental concerns.

Our paper leaves room for future research, we have considered a monopolist airport but the model could benefit from a relaxation of this assumption. Also, we have considered a private airport but perhaps a public could provide further incentives for airlines to use SAFs.

References

Armstrong, M. (2006). Competition in two-sided markets. *The RAND Journal of Economics*, *37*(3), 668–691. Retrieved from http://www.jstor.org/stable/25046266

Dobruszkes, F., Dehon, C., & Givoni, M. (2014). Does European high-speed rail affect the current level of air services? An EU-wide analysis. *Transportation Research Part A: Policy and Practice*, *69*, 461-475. doi: https://doi.org/10.1016/j.tra.2014.09.004

D'Alfonso, T., Jiang, C., & Bracaglia, V. (2015). Would competition between air transport and high-speed rail benefit environment and social welfare? *Transportation Research Part B: Methodological*, *74*, 118-137. doi: https://doi.org/10.1016/j.trb.2015.01.007

D'Alfonso, T., Jiang, C., & 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. doi: https://doi.org/10.1016/j.tra.2016.06.009

EASA. (2022a). *European Aviation Environmental Report* (Tech. Rep.). European Union Aviation Safety Agency-European Environment Agency.

EASA. (2022b). *Panel 5: Airports as an Enabler of Greener Aviation.* Annual Safety Conference. Retrieved from https://www.easa.europa.eu/en/downloads/137429/en

EIB. (2020). *The EIB Climate Survey 2019-2020 — how citizens are confronting the climate crisis and what actions they expect from policy makers and businesses* (Tech. Rep.). European Investment Bank, Luxembourg. Retrieved from https://www.eib.org/attachments/thematic/the_eib_climate_survey_2019_2020_en.pdf

European Commission. (2017). *Proposal for a Regulation of the European Parliament and of the Council* (Tech. Rep.). EU: European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017SC0031&from=EN.

European Parlament and of the Council. (2009). *Directive 2009/12/EC.* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0012.

Flores-Fillol, R., Iozzi, A., & Valletti, T. (2018). Platform pricing and consumer foresight: The case of airports. *Journal of Economics & Management Strategy*, *27*(4), 705-725. doi: https://doi.org/10.1111/jems.12253

Friederiszick, H. W., Gantumur, T., Jayaraman, R., Röller, L.-H., & Weinmann, J. (2009).

Railway alliances in EC long-distance passenger transport: A competitive assessment post-liberalization 2010 (Tech. Rep. No. No. WP-109-01). ESMT European School of Management and Technology. Retrieved from https://www.e-ca.com/wp-content/uploads/2009_wp-109-01.pdf

Gillen, D. (2011). The evolution of airport ownership and governance. *Journal of Air Transport Management*, *17*(1), 3-13. Retrieved from https://EconPapers.repec.org/RePEc:eee:jaitra:v:17:y:2011:i:1:p:3-13

Givoni, M., Dobruszkes, F., & Lugo, I. (2012). Uncovering the real potential for air–rail substitution: An exploratory analysis. In *Energy, transport, & the environment: Addressing the sustainable mobility paradigm* (pp. 495–512). London: Springer London. doi: 10.1007/978-1-4471-2717-8_27

Hoernig, S. (2015). *Three equivalent Salop models and their normative representative consumer* (Nova SBE Working Paper Series No. wp593). Universidade Nova de Lisboa, Nova School of Business and Economics. Retrieved from https://ideas.repec.org/p/unl/unlfep/wp593.html

ICAO. (2019a). *Future of Aviation.* International Civil Aviation Organization. Retrieved from https://www.icao.int/Meetings/FutureOfAviation/Pages/default.aspx

ICAO. (2019b). *Introduction to the ICAO Basket of Measures to Mitigate Climate Change* (Tech. Rep.). International Civil Aviation Organization. Retrieved from https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg111-115.pdf

ICCT. (2022). *Leveraging EU policies and climate ambition to close the cost gap between conventional and Sustainable Aviation Fuels* (Tech. Rep.). International Council on Clean Transportation.

Jiang, C., & Zhang, A. (2016). Airline network choice and market coverage under high-speed rail competition. *Transportation Research Part A: Policy and Practice*, *92*, 248-260. doi: https://doi.org/10.1016/j.tra.2016.06.008

Koech, A. K., Buyle, S., & Macário, R. (2023). Airline brand awareness and perceived quality effect on the attitudes towards frequent-flyer programs and airline brand choice - moderating effect of frequent-flyer programs. *Journal of Air Transport Management*, *107*, 102342. doi: https://doi.org/10.1016/j.jairtraman.2022.102342

Malavolti, E. (2016). Single till or dual till at airports: A two-sided market analysis. *Transportation Research Procedia*, *14*, 3696-3703. doi: https://doi.org/10.1016/j.trpro.2016.05.489

Malavolti, E., & Marty, F. (2019). Faut-il autoriser des aides d'exploitation pérennes versées par les aéroports régionaux aux compagnies à bas coûts? *Revue économique*, *70*(2), 149-166. doi: https://doi.org/10.3917/reco.pr2.0129

Martimort, D., Pommey, G., & Pouyet, J. (2022). Optimal regulation design of airports: Investment incentives and impact of commercial services. *Transportation Research Part B: Methodological*, *164*, 25-44. doi: https://doi.org/10.1016/j.trb.2022.07.008

Mayeres, I., Proost, S., Delhaye, E., Novelli, P., Conijn, S., Gómez-Jiménez, I., & Rivas-Brousse, D. (2023). Climate ambitions for european aviation: Where can sustainable aviation fuels bring us? *Energy Policy*, *175*, 113502. doi: https://doi.org/10.1016/j.enpol.2023.113502

McKinsey & Company. (2022). *Boosting passenger preference for rail* (Tech. Rep.). Paris: Author. Retrieved from https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/boosting-passenger-preference-for-rail

OFS. (2022). *Coûts et financement des transports 2019: Transport routier, ferroviaire et aérien* (Tech. Rep.). Office fédéral de la statistique.

PwC. (2022). *The real cost of green aviation: Evaluation of SAF ramp-up scenarios and cost implications for the European aviation sector* (Tech. Rep.). Germany: PwC Strategy. Retrieved from https://www.pwc.com/gx/en/issues/esg/the-energy-transition/sustainable-aviation-fuels-cost-less-than-you-think.html

Rochet, J.-C., & Tirole, J. (2006). Two-sided markets: A progress report. *The RAND Journal of Economics*, *37*(3), 645–667. Retrieved 2023-01-24, from http://www.jstor.org/stable/25046265

Salop, S. C. (1979). Monopolistic competition with outside goods. *The Bell Journal of Economics*, *10*(1), 141–156. Retrieved from http://www.jstor.org/stable/3003323

Thessaloniki Forum of Airport Charges. (2021). *Airport Charges and Environmental issues and considerations.* https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.cnmc.es/file/300918/download&ved=2ahUKEwifkOmIg5OIAxWAUqQEHZqbC5OQFnoECBMQAQ&usg=AOvVaw0hhMOXFHw

-sKgpRuEu3cUF.

Wang, C., Jiang, C., & Zhang, A. (2021). Effects of Airline Entry on High-Speed Rail. *Transportation Research Part B: Methodological*, *154*, 242-265. doi: https://doi.org/10.1016/j.trb.2021.10.004

Yang, H., & Zhang, A. (2012). Effects of high-speed rail and air transport competition on prices, profits and welfare. *Transportation Research Part B: Methodological*, *46*(10), 1322-1333. doi: https://doi.org/10.1016/j.trb.2012.09.001

A Appendix

A.1 Proof of Lemma 1

We solve airline 1, airline 2, and the train operator program and look for the equilibrium ticket prices. In stage 2, the three firms compete in prices. Firms' k program writes:

$$\underset{\{p_k\}}{Max} \quad \pi_K = D_k(p_k - c_k) - F\mathbb{1}_{k=\{1,2\}}$$

with c_k the variable costs of firm k.

The equilibrium prices are:

$$p_1(\alpha)^* = p_2(\alpha)^* = \frac{4\alpha + c_T}{5} + \frac{t}{3}$$

$$p_3(\alpha)^* = \frac{2\alpha + 3c_T}{5} + \frac{t}{3}$$

the equilibrium quantities are:

$$D_1(\alpha)^* = D_2(\alpha)^* = \frac{c_T - \alpha}{5t} + \frac{1}{3}$$

$$D_3(\alpha)^* = \frac{2(\alpha - c_T)}{5t} + \frac{1}{3}$$

Notice that if the per unit charge set by the airport is $\alpha \leq c_T - \frac{5t}{6}$, then we have $D_3(\alpha)^* = 0$. Otherwise, if $c_T + \frac{5t}{3} \leq \alpha$, then we have $D_1(\alpha)^* = D_2(\alpha)^* = 0$. $\square$

A.2 Proof of Lemma 2

We solve the airport program and look for the equilibrium aeronautical charges and rent. We have $p(\alpha) = p_1(\alpha) = p_2(\alpha)$, thus we can combine PC1 and PC2 in one constraint:

$$\frac{p(\alpha) - \alpha}{2} D_A(\alpha) \geq F$$

The Lagrangian is:

$$\mathcal{L} = D_A(\alpha)(\alpha - f) + 2F + rS(D_A(\alpha), r) + \lambda[\frac{p(\alpha) - \alpha}{2} D_A(\alpha) - F]$$

the constraint is saturated ($\lambda = 2 > 0$), i.e., the airport extracts all the airlines' profits:

$$\frac{p(\alpha) - \alpha}{2} D_A(\alpha) = F$$

Then, we can directly replace F in the airport's program:

$$Max \quad \underset{\{\alpha,r\}}{\pi_A} = D_A(\alpha)(p(\alpha) - f) + r[\gamma D_A(\alpha) - r]$$

The first-order conditions give:

$$\frac{\partial \pi_A}{\partial \alpha} = 0 \iff \underbrace{\frac{\partial D_A(\alpha)}{\partial \alpha}(p(\alpha) - f + r\gamma)}_{<0 \iff \frac{\partial D_A(\alpha)}{\partial \alpha} = \frac{-2}{5t}} + \underbrace{D_A(\alpha)\frac{\partial p(\alpha)}{\partial \alpha}}_{>0 \iff \frac{\partial p(\alpha)}{\partial \alpha} = \frac{4}{5}} = 0 \tag{1}$$

$$\frac{\partial \pi_A}{\partial r} = 0 \iff r = \frac{\gamma D_A(\alpha)}{2} \tag{2}$$

We can combine 1 and 2 into a single equation:

$$\underbrace{\frac{\partial D_A(\alpha)}{\partial \alpha}(p(\alpha) - f + \gamma^2 \frac{D_A(\alpha)}{2})}_{<0 \iff \frac{\partial D_A(\alpha)}{\partial \alpha} = \frac{-2}{5t}} + \underbrace{D_A(\alpha)\frac{\partial p(\alpha)}{\partial \alpha}}_{>0 \iff \frac{\partial p(\alpha)}{\partial \alpha} = \frac{4}{5}} = 0$$

$$\iff \underbrace{\frac{\partial D_A(\alpha)}{\partial \alpha}(p(\alpha) - f)}_{<0 \iff \frac{\partial D_A(\alpha)}{\partial \alpha} = \frac{-2}{5t}} + \underbrace{D_A(\alpha)(\frac{\partial p(\alpha)}{\partial \alpha} + \frac{\gamma^2}{2}\frac{\partial D_A(\alpha)}{\partial \alpha})}_{>0 \quad \text{if} \quad 2t > \gamma^2} = 0$$

$$\iff \frac{-2}{5t}\Big(\frac{4\alpha + c_T}{5} + \frac{t}{3} - f\Big) + \Big(\frac{2(c_T - \alpha)}{5t} + \frac{2t}{3}\Big)\Big(\frac{4t - 2\gamma^2}{5t}\Big) = 0 \tag{3}$$

We verify the second-order conditions:

$$\frac{\partial^2 \pi_A}{\partial \alpha^2} = \frac{-16}{25t} < 0$$

$$\frac{\partial^2 \pi_A}{\partial r^2} = -2 < 0$$

Solving we retrieve the equilibrium aeronautical charges and rent set by the airport :

$$\alpha^* = \frac{(3t - \gamma^2)(3c_T + 5t) + 15ft}{3(8t - \gamma^2)}$$

$$r^* = \frac{\gamma(3(c_T - f) + 5t)}{3(8t - \gamma^2)}$$

$$F^* = \frac{t(3(c_T - f) + 5t)^2}{9(8t - \gamma^2)^2}$$

Notice that:

$$\frac{\partial \alpha}{\partial \gamma} = \frac{-10t\gamma(3(c_T - f) + 5t)}{3(8t - \gamma^2)^2} < 0$$

$$\frac{\partial r}{\partial \gamma} = \frac{(8t + \gamma^2)(3(c_T - f) + 5t)}{3(8t - \gamma^2)^2} > 0$$

$$\frac{\partial F}{\partial \gamma} = \frac{4t\gamma(3(c_T - f) + 5t)^2}{9(8t - \gamma^2)^3} > 0 \quad \text{if} \quad 8t > \gamma^2$$

We compute the airport's, airlines, and train operator's profits:

$$\pi_A^* = \frac{(3(c_T - f) + 5t)^2}{9(8t - \gamma^2)}$$

$$\pi_1^* = \pi_2^* = 0$$

$$\pi_3^* = \frac{t(14t - 3(2(c_T - f) + \gamma^2))^2}{9(8t - \gamma^2)^2}$$

The number of passengers visiting the airport and the train station is respectively:

$$D_A^* = \frac{2(3(c_T - f) + 5t)}{3(8t - \gamma^2)} > 0 \quad \text{if} \quad 8t > \gamma^2$$

$$D_3^* = 1 - \frac{2(3(c_T - f) + 5t)}{3(8t - \gamma^2)}$$

provided that the disutility from not traveling with their preferred means of travel is large enough $t > \hat{t} = \frac{\gamma^2}{8}$, then the demand addressed to the airport is positive. Else, $t \leq \hat{t}$ passengers can only travel by train.

A.3 Proof of Lemma 3

We solve airline 1, airline 2, and the train operator program and look for the equilibrium ticket prices. In stage 2, the three firms compete in prices. Firms' k program writes:

$$\underset{\{p_k\}}{Max} \quad \pi_K = D_k(p_k - c_k) - F\mathbb{1}_{k=\{1,2\}}$$

with

$$c_k = \begin{cases} \alpha \quad \text{if} \quad k = 1 \\ \delta c_{SAF} + \alpha \quad \text{if} \quad k = 2 \\ c_T \quad \text{if} \quad k = 3 \end{cases}$$

The equilibrium prices are:

$$p_1(\alpha)^u = \frac{4\alpha + c_T + \delta(c_{SAF} + t)}{5} + \frac{t}{3}$$

$$p_2(\alpha)^u = \frac{4\alpha + c_T + 3\delta c_{SAF}}{5} + \frac{t}{3}$$

$$p_3(\alpha)^u = \frac{2\alpha + 3c_T + \delta(c_{SAF} - t)}{5} + \frac{t}{3}$$

the equilibrium quantities are:

$$D_1(\alpha)^u = \frac{c_T - \alpha + \delta(c_{SAF} + t)}{5t} + \frac{1}{3}$$

$$D_2(\alpha)^u = \frac{c_T - \alpha - 2\delta c_{SAF}}{5t} + \frac{1}{3}$$

$$D_3(\alpha)^u = \frac{2(\alpha - c_T) + 3\delta(c_{SAF} - t)}{5t} + \frac{1}{3}$$

Here, if $\alpha > c_T + \delta(c_{SAF} + t) + \frac{5t}{3}$, then we have $D_1(\alpha)^u = 0$ and $D_2(\alpha)^u < 0$. If $\delta c_{SAF} > t(5-3\delta)$ and $c_T+\delta(c_{SAF}+t)+\frac{5t}{3} > \alpha > c_T-2\delta c_{SAF}+\frac{5t}{3} > c_T-\frac{3\delta(c_{SAF}-t)}{2}-\frac{5t}{6}$, then $D_2(\alpha)^u = 0$. Else, if $\delta c_{SAF} < t(5-3\delta)$ and $c_T + \delta(c_{SAF}+t) + \frac{5t}{3} > \alpha > c_T - \frac{3\delta(c_{SAF}-t)}{2} - \frac{5t}{6} c_T - 2\delta c_{SAF} + \frac{5t}{3}$, then $D_2(\alpha)^u = 0$. Otherwise, if $c_T - \frac{3\delta(c_{SAF}-t)}{2} - \frac{5t}{6} > \alpha$, then $D_3(\alpha)^u = 0$.

A.4 Proof of Proposition 1

We solve the airport program and look for the equilibrium aeronautical charges and rent. First, we consider the case in which the airport only serves airline 1 (Case 1.). There are two possibilities regarding the passengers who otherwise would have chosen to travel with airline 2. Either they may choose not to travel at all leaving the market uncovered (Case 1.a.), or they may shift to airline 1 or the train (Case 1.b.).

A.4.1 Case 1: The airport only serves airline 1

Case 1.a. In this case, the market is uncovered, meaning that not all passengers travel with a firm. Namely, the demands from A.3 remain unchanged but the airport excludes airline 2 from the market leading to $\delta = 0$. In this case, $D_2(\alpha)$ is not taken into account in the airport's program. In stage 1, the airport sets the aeronautical charges for airlines and the rent for shops:

$$\underset{\{\alpha,r,F\}}{Max} \quad \pi_A = D_A(\alpha)(\alpha - f) + F + rS(D_A(\alpha), r)$$

$$\text{s.t.} \quad D_1(\alpha) = D_A(\alpha)$$

$$D_1(\alpha)(p_1(\alpha) - \alpha) = F$$

The Lagrangian is:

$$\mathcal{L} = D_1(\alpha)(\alpha - f) + F + rS(D_1(\alpha), r) + \lambda_1[(p_1(\alpha) - \alpha - c)D_1(\alpha) - F]$$

the constraint is saturated ($\lambda_1 = 1 > 0$), i.e., the airport extracts all the airlines' profits:

$$(p_1(\alpha) - \alpha)D_1(\alpha) = F$$

Then, we can directly replace F in the airport's program:

$$Max \quad \underset{\{\alpha,r\}}{\pi_A} = D_1(\alpha)(p_1(\alpha) - f) + r[\gamma D_1(\alpha) - r]$$

The first order conditions give:

$$\frac{\partial \pi_A}{\partial \alpha} = 0 \iff \underbrace{\frac{\partial D_1(\alpha)}{\partial \alpha}(p_1(\alpha) - f + r\gamma)}_{<0 \iff \frac{\partial D_1(\alpha)}{\partial \alpha} = \frac{-1}{5t}} + \underbrace{D_1(\alpha)\frac{\partial p_1(\alpha)}{\partial \alpha}}_{>0 \iff \frac{\partial p_1(\alpha)}{\partial \alpha} = \frac{4}{5}} = 0 \tag{4}$$

$$\frac{\partial \pi_A}{\partial r} = 0 \iff r = \frac{\gamma D_1(\alpha)}{2} \tag{5}$$

We can combine 4 and 5 into a single equation:

$$\underbrace{\frac{\partial D_1(\alpha)}{\partial \alpha}(p_1(\alpha) - f + \gamma^2 \frac{D_1(\alpha)}{2})}_{<0 \iff \frac{\partial D_1(\alpha)}{\partial \alpha} = \frac{-1}{5t}} + \underbrace{D_1(\alpha)\frac{\partial p_1(\alpha)}{\partial \alpha}}_{>0 \iff \frac{\partial p_1(\alpha)}{\partial \alpha} = \frac{4}{5}} = 0$$

$$\iff \underbrace{\frac{\partial D_1(\alpha)}{\partial \alpha}(p_1(\alpha) - f)}_{<0 \iff \frac{\partial D_1(\alpha)}{\partial \alpha} = \frac{-1}{5t}} + \underbrace{D_1(\alpha)(\frac{\partial p_1(\alpha)}{\partial \alpha} + \frac{\gamma^2}{2}\frac{\partial D_1(\alpha)}{\partial \alpha})}_{>0 \quad \text{if} \quad 4t > \gamma^2} = 0$$

$$\iff \frac{-1}{5t}\left(\frac{4\alpha + c_T}{5} + \frac{t}{3} - f\right) + \left(\frac{c_T - \alpha}{5t} + \frac{1}{3}\right)\left(\frac{4t - \gamma^2}{5t}\right) = 0 \tag{6}$$

We verify the second-order conditions:

$$\frac{\partial^2 \pi_A}{\partial \alpha^2} = \frac{-8}{25t} < 0$$

$$\frac{\partial^2 \pi_A}{\partial r^2} = -2 < 0$$

Solving we retrieve the equilibrium aeronautical charges and rent set by the airport :

$$\alpha^{u1a} = \frac{30tf + (6t - \gamma^2)(3c_T + 5t)}{3(16t - \gamma^2)}$$

$$r^{u1a} = \frac{\gamma(3(c_T - f) + 5t)}{3(16t - \gamma^2)}$$

$$F^{u1a} = \frac{4t(3(c_T - f) + 5t)^2}{9(16t - \gamma^2)^2}$$

The demands addressed to the airport and train are respectively:

$$D_A^{u1a} = D_1^{u1a} = \frac{2(3(c_T - f) + 5t))}{3(16t - \gamma^2)}$$

$$D_3^{u1a} = 1 - \frac{4(3(c_T - f) + 5t)}{3(16t - \gamma^2)}$$

The equilibrium tickets prices are:

$$p_1^{u1a} = \frac{24ft + (3c_T + 5t)(8t - \gamma^2)}{3(16t - \gamma^2)}$$

$$p_3^{u1a} = c_T + t - \frac{4t(3(c_T - f) + 5t))}{3(16t - \gamma^2)}$$

We compute the airport's, airlines, and train operator's profits:

$$\pi_A^{u1a} = \frac{(3(c_T - f) + 5t)^2}{9(16t - \gamma^2)}$$

$$\pi_1^{u1a} = 0$$

$$\pi_3^{u1a} = \frac{t(12(c_T - f) + 28t - 3\gamma^2)^2}{9(16t - \gamma^2)^2}$$

Case 1. b. In this case, the market is covered, meaning that all passengers travel with a firm. Thus, passengers that otherwise would travel with firm 2 shift to airline 1 or the train. Notice that this case is equivalent to a Hoteling model with predetermined asymmetric locations. Namely, the airline would be located at 0 and 1 while the train at $\frac{2}{3}$. First, let us consider the consumers located in the segment $x \in [0; \frac{2}{3}]$, we define $x\hat{_{1,3}}$ the consumer indifferent between traveling with airline 1 or taking the train:

$$x\hat{_{1,3}} = \frac{p3 - p1}{2t} + \frac{1}{3}$$

Second, let us consider the consumers located in the segment $x \in [\frac{2}{3}; 1]$, we define $x\hat{_{3,1}}$ the consumer indifferent between taking the train or traveling with airline 1:

$$x\hat{_{3,1}} = \frac{p1 - p3}{2t} + \frac{1}{3}$$

The demand functions are:

$$D_k = \begin{cases} \frac{t+p_3-p_1}{t} \quad \text{if} \quad k = 1 \\ \\ \frac{p_1-p_3}{t} \quad \text{if} \quad k = 3 \end{cases}$$

In stage 2, the three firms compete in prices. Firms' k program writes:

$$\underset{\{p_k\}}{Max} \quad \pi_K = D_k(p_k - c_k) - F\mathbb{1}_{k=\{1,2\}}$$

The equilibrium prices are:

$$p_1(\alpha)^{u1b} = \frac{2(\alpha + t) + c_T}{3}$$

$$p_3(\alpha)^{u1b} = \frac{\alpha + 2c_T + t}{3}$$

the equilibrium quantities are:

$$D_1(\alpha)^{u1b} = \frac{c_T - \alpha + 2t}{3t}$$

$$D_3(\alpha)^{u1b} = \frac{\alpha - c_T + t}{3t}$$

and profits:

$$\pi_1(\alpha)^{u1b} = \frac{(c_T - \alpha + 2t)^2}{9t} - F$$

$$\pi_3(\alpha)^{u1b} = \frac{(\alpha - c_T + t)^2}{9t}$$

In stage 1, the airport sets the aeronautical charges for airlines and the rent for shops: We retrieve the following equilibrium aeronautical charges and rent set by the airport :

$$\alpha^{u1b} = \frac{6tf + (2t - \gamma^2)(c_T + 2t)}{8t - \gamma^2}$$

$$r^{u1b} = \frac{\gamma(c_T - f + 2t)}{8t - \gamma^2}$$

$$F^{u1b} = \frac{4t(c_T - f + 2t)^2}{(8t - \gamma^2)^2}$$

The demands addressed to the airport and train are respectively:

$$D_A^{u1b} = D_1^{u1b} = \frac{2(c_T - f + 2t)}{8t - \gamma^2}$$

$$D_3^{u1b} = 1 - \frac{2(c_T - f + 2t)}{8t - \gamma^2}$$

The equilibrium tickets prices are:

$$p_1^{u1a} = \frac{4ft + (c_T + 2t)(4t - \gamma^2)}{8t - \gamma^2}$$

$$p_3^{u1b} = c_T + t - \frac{2t(c_T - f + 2t)}{8t - \gamma^2}$$

We compute the airport's, airlines, and train operator's profits:

$$\pi_A^{u1b} = \frac{(c_T - f + 2t)^2}{8t - \gamma^2}$$

$$\pi_1^{u1b} = 0$$

$$\pi_3^{u1b} = \frac{t(2(c_T - f - 2t) - \gamma^2)^2}{(8t - \gamma^2)^2}$$

A.4.2 Case 2: The airport serves both airlines

Second, we write the airport program when it serves both airlines:

$$Max \quad \underset{\{\alpha,r,F\}}{\pi_A} = D_A(\alpha)(\alpha - f) + F + rS(D_A(\alpha), r)$$

$$\text{s.t.} \quad D_1(\alpha) + D_2(\alpha) = D_A(\alpha)$$

$$D_2(\alpha)(p_2(\alpha) - \alpha - \delta c_{SAF}) = F$$

The Lagrangian is:

$$\mathcal{L} = [D_1(\alpha)+D_2(\alpha)](\alpha-f)+2F+r(\gamma[D_1(\alpha)+D_2(\alpha)]-r)+\lambda_2[(p_2(\alpha)-\alpha-\delta c_{SAF})D_2(\alpha)-F]$$

the constraint is saturated ($\lambda_2 = 2 > 0$), i.e., the airport extracts all the airlines' profits:

$$(p_2(\alpha) - \alpha - \delta c_{SAF})D_2(\alpha) = F$$

Then, we can directly replace F in the airport's program:

$$Max \quad \underset{\{\alpha,r\}}{\pi_A} = D_1(\alpha)(\alpha - f + r\gamma) + D_2(\alpha)(2p_2(\alpha) - f - \alpha - 2\delta c_{SAF} + r\gamma) - r^2$$

The first order conditions give:

$$\frac{\partial \pi_A}{\partial \alpha} = 0 \iff \underbrace{\frac{\partial D_1(\alpha)}{\partial \alpha}}_{=\frac{-1}{5t}<0}(\alpha - f + r\gamma) + D_1(\alpha)$$
$$+ \underbrace{\frac{\partial D_2(\alpha)}{\partial \alpha}}_{=\frac{-1}{5t}<0}(2p_2(\alpha) - f - \alpha - 2\delta c_{SAF} + r\gamma) + D_2(\alpha)(\underbrace{\frac{2\partial p_2(\alpha)}{\partial \alpha}}_{=\frac{4}{5}>0} - 1) = 0 \quad (7)$$

$$\iff \underbrace{\frac{-2}{5t}(p_2(\alpha) - f - \delta c_{SAF} + r\gamma)}_{<0} + \underbrace{D_1(\alpha) + \frac{3}{5}D_2(\alpha)}_{>0} = 0$$

$$\frac{\partial \pi_A}{\partial r} = 0 \qquad \iff r = \frac{\gamma[D_1(\alpha) + D_2(\alpha)]}{2} \quad (8)$$

We can combine 7 and 8 into a single equation:

$$\iff \underbrace{\frac{-2}{5t}(p_2(\alpha) - f - \delta c_{SAF})}_{<0} + \underbrace{D_1(\alpha)(\frac{5t-2\gamma^2}{5t})}_{>0 \quad \text{if} \quad 5t>2\gamma^2} \underbrace{D_2(\alpha)(\frac{3t-2\gamma^2}{5t})}_{>0 \quad \text{if} \quad 5t>2\gamma^2} = 0$$

We verify the second-order conditions:

$$\frac{\partial^2 \pi_A}{\partial \alpha^2} = \frac{-16}{25t} < 0$$

$$\frac{\partial^2 \pi_A}{\partial r^2} = -2 < 0$$

Solving we get:

$$\alpha^{u2} = \frac{30ft + 2(3t-\gamma^2)(3c_T + 5t) + 3\delta(t(5t-\gamma^2) + c_{SAF}(3t+\gamma^2))}{6(8t-\gamma^2)}$$

$$r^{u2} = \frac{\gamma(10(3(c_T - f) + 5t) + 3\delta(3t - 11c_{SAF}))}{30(8t-\gamma^2)}$$

$$F^{u2} = \frac{1}{900t(8t-\gamma^2)^2}\Big(10t(3(c_T - f) + 5t) - 3\delta(c_{SAF}(35t-\gamma^2) + t(5t-\gamma^2))\Big)^2$$

The demand addressed to the airport is:

$$D_A^{u2} = \frac{10(3(c_T - f) + 5t) + 3\delta(3t - 11c_{SAF})}{15(8t - \gamma^2)}$$

We compute the airport's, airlines, and train operator's profits:

$$\pi_A^{u2} = \pi_A^* + \frac{\delta(3(c_T - f) + 5t)(3t - 11c_{SAF})}{15(8t - \gamma^2)} + 9\delta^2\Big(5t(c_{SAF}(53c_{SAF} + 6t) + 5t^2)$$

$$-2\gamma^2(3c_{SAF} + t)^2\Big)$$

$$\pi_1^{u2} = \frac{\delta(3c_{SAF} + t)(10(3(c_T - f) + 5t) + 3\delta(3t - 11c_{SAF}))}{75(8t - \gamma^2)}$$

$$\pi_2^{u2} = 0$$

$$\pi_3^{u2} = \frac{(t(10(3(c_T - f) - 7t) + 3(5\gamma^2 + 3\delta(3t - 11c_{SAF})))^2}{225t(8t - \gamma^2)^2}$$

A.5 Proof of Lemma 4

We solve airline 1, airline 2, and the train operator program and look for the equilibrium ticket prices. In stage 2, the three firms compete in prices. Firms' k program writes:

$$\underset{\{p_k\}}{Max} \quad \pi_K = D_k(p_k - c_k) - F\mathbb{1}_{k=\{1,2\}}$$

with

$$c_k = \begin{cases} \alpha_1 \quad \text{if} \quad k = 1 \\ \delta c_{SAF} + \alpha_2 \quad \text{if} \quad k = 1 \\ c_T \quad \text{if} \quad k = 3 \end{cases}$$

The equilibrium prices are:

$$p_1(\alpha_1, \alpha_2)^D = \frac{c_T + 3\alpha_1 + \alpha_2 + \delta(c_{SAF} + t)}{5} + \frac{t}{3}$$

$$p_2(\alpha_1, \alpha_2)^D = \frac{c_T + \alpha_1 + 3\alpha_2 + 3\delta c_{SAF}}{5} + \frac{t}{3}$$

$$p_3(\alpha_1, \alpha_2)^D = \frac{3c_T + \alpha_1 + \alpha_2 + \delta(c_{SAF} - t)}{5} + \frac{t}{3}$$

the equilibrium quantities are:

$$D_1(\alpha_1, \alpha_2)^D = \frac{c_T - 2\alpha_1 + \alpha_2 + \delta(c_{SAF} + t)}{5t} + \frac{1}{3}$$

$$D_2(\alpha_1, \alpha_2)^D = \frac{c_T + \alpha_1 - 2\alpha_2 - 2\delta c_{SAF}}{5t} + \frac{1}{3}$$

$$D_3(\alpha_1, \alpha_2)^D = \frac{\alpha_1 + \alpha_2 - 2c_T + \delta(c_{SAF} - t)}{5t} + \frac{1}{3}$$

A.6 Proof of Proposition 2

We solve the airport program and look for the equilibrium aeronautical charges and rent.

$$Max \underset{\{\alpha_1,\alpha_2,r,F_1,F_2\}}{\pi_A} = D_1(\alpha_1,\alpha_2)(p_1(\alpha_1,\alpha_2)-f)+D_2(\alpha_1,\alpha_2)(p_2(\alpha_1,\alpha_2)-f)+F_1+F_2+rS(D_A(\alpha_1,\alpha_2),r)$$

$$\text{s.t.} \quad D_1(\alpha_1, \alpha_2)(p_1(\alpha_1, \alpha_2) - \alpha_1) \geq F_1 \qquad \text{(PC1)}$$

$$D_2(\alpha_1, \alpha_))(p_2(\alpha_1, \alpha_2) - \alpha_2 - \delta c_{SAF}) \geq F_2 \qquad \text{(PC2)}$$

The Lagrangian is:

$$\mathcal{L} = D_1(\alpha_1, \alpha_2)(p_1(\alpha_1, \alpha_2) - f) + D_2(\alpha_1, \alpha_2)(p_2(\alpha_1, \alpha_2) - f) + F_1 + F_2$$

$$+rS(D_A(\alpha_1, \alpha_2), r) + \mu_1[D_1(\alpha_1, \alpha_2)(p_1(\alpha_1, \alpha_2) - \alpha_1) - F_1]$$

$$+\mu_2[D_2(\alpha_1, \alpha_2)(p_2(\alpha_1, \alpha_2) - \alpha_2 - \delta c_{SAF}) - F_2]$$

both constraints are saturated ($\mu_1 = 1 > 0$ and $\mu_2 = 1 > 0$), i.e., the airport extracts all the airlines' profits:

$$D_1(\alpha_1,\alpha_2)(p_1(\alpha_1,\alpha_2)-\alpha_1)=F_1$$

$$D_2(\alpha_1,\alpha_))(p_2(\alpha_1,\alpha_2)-\alpha_2-\delta c_{SAF})=F_2$$

Then, we can directly replace F_1 and F_2 in the airport's program:

$$\underset{\{\alpha_1,\alpha_2,r\}}{Max}\quad \pi_A = D_1(\alpha_1,\alpha_2)(p_1(\alpha_1,\alpha_2)-f+\gamma r)+D_2(\alpha_1,\alpha_2)(p_2(\alpha_1,\alpha_2)-f-\delta c_{SAF}+\gamma r)-r^2$$

The first order conditions give:

$$\begin{aligned}\frac{\partial \pi_A}{\partial \alpha_1}=0 \iff & \underbrace{\frac{\partial D_1(\alpha_1,\alpha_2)}{\partial \alpha_1}}_{=\frac{-2}{5t}<0}(p_1(\alpha_1,\alpha_2)-f+r\gamma)+D_1(\alpha_1,\alpha_2)\underbrace{\frac{\partial p_1(\alpha_1,\alpha_2)}{\partial \alpha_1}}_{=\frac{3}{5}>0}\\ &+\underbrace{\frac{\partial D_2(\alpha_1,\alpha_2)}{\partial \alpha_1}}_{=\frac{1}{5t}>0}(p_2(\alpha_1,\alpha_2)-f-\delta c_{SAF}+r\gamma)+D_2(\alpha_1,\alpha_2)\underbrace{\frac{\partial p_2(\alpha_1,\alpha_2)}{\partial \alpha_1}}_{=\frac{1}{5}>0}=0 \end{aligned} \quad (9)$$

$$\begin{aligned}\frac{\partial \pi_A}{\partial \alpha_2}=0 \iff & \underbrace{\frac{\partial D_1(\alpha_1,\alpha_2)}{\partial \alpha_2}}_{=\frac{1}{5t}>0}(p_1(\alpha_1,\alpha_2)-f+r\gamma)+D_1(\alpha_1,\alpha_2)\underbrace{\frac{\partial p_1(\alpha_1,\alpha_2)}{\partial \alpha_2}}_{=\frac{1}{5}>0}\\ &+\underbrace{\frac{\partial D_2(\alpha_1,\alpha_2)}{\partial \alpha_2}}_{=\frac{-2}{5t}<0}(p_2(\alpha_1,\alpha_2)-f-\delta c_{SAF}+r\gamma)+D_2(\alpha_1,\alpha_2)\underbrace{\frac{\partial p_2(\alpha_1,\alpha_2)}{\partial \alpha_2}}_{=\frac{3}{5}>0}=0 \end{aligned} \quad (10)$$

$$\frac{\partial \pi_A}{\partial r}=0 \qquad \iff r=\frac{\gamma[D_1(\alpha_1,\alpha_2)+D_2(\alpha_1,\alpha_2)]}{2} \quad (11)$$

We can plug equation 11 into equations 9 and 10:

$$\begin{aligned}&\underbrace{\frac{-2}{5t}(p_1(\alpha_1,\alpha_2)-f)}_{<0}+\underbrace{\frac{1}{5t}(p_2(\alpha_1,\alpha_2)-f-\delta c_{SAF})}_{>0}\\ &\qquad +\underbrace{D_1(\alpha_1,\alpha_2)\left(\frac{6t-\gamma^2}{10t}\right)}_{\text{if}\quad 6t>\gamma^2}+\underbrace{D_2(\alpha_1,\alpha_2)\left(\frac{2t-\gamma^2}{10t}\right)}_{\text{if}\quad 2t>\gamma^2}=0\end{aligned} \quad (12)$$

$$\underbrace{\frac{1}{5t}(p_1(\alpha_1,\alpha_2)-f)}_{>0}+\underbrace{\frac{-2}{5t}(p_2(\alpha_1,\alpha_2)-f-\delta c_{SAF})}_{<0}$$

$$+\underbrace{D_1(\alpha_1,\alpha_2)\Big(\frac{2t-\gamma^2}{10t}\Big)}_{\text{if} \quad 2t>\gamma^2}+\underbrace{D_2(\alpha_1,\alpha_2)\Big(\frac{6t-\gamma^2}{10t}\Big)}_{\text{if} \quad 6t>\gamma^2}=0 \quad (13)$$

We verify the second-order conditions:

$$\frac{\partial^2\pi_A}{\partial\alpha_1^2}=\frac{-2}{5t}<0$$

$$\frac{\partial^2\pi_A}{\partial\alpha_2^2}=\frac{-2}{5t}<0$$

$$\frac{\partial^2\pi_A}{\partial r^2}=-2<0$$

Solving we retrieve the equilibrium aeronautical charges and rent set by the airport :

$$\alpha_1^D=\frac{8(15ft+(3t-\gamma^2)(3c_T+5t)+3\delta(t(12t-\gamma^2)+c_{SAF}(20t-\gamma^2))}{24(8t-\gamma^2)}$$

$$\alpha_2^D=\frac{8(15ft+(3t-\gamma^2)(3c_T+5t)-3\delta(t(28t-\gamma^2)+c_{SAF}(28t-\gamma^2))}{24(8t-\gamma^2)}$$

$$r^D=\frac{\gamma(2(3(c_T-f)+5t)-3\delta(c_{SAF}-t))}{6(8t-\gamma^2)}$$

$$F_1^D=\frac{1}{576t(8t-\gamma^2)^2}\Big(8t(3(c_T-f)+5t)+3\delta(c_{SAF}(20t-3\gamma^2)+t(12t-\gamma^2))\Big)^2$$

$$F_2^D=\frac{1}{576t(8t-\gamma^2)^2}\Big(8t(3(c_T-f)+5t)-3\delta(c_{SAF}(28t-3\gamma^2)+t(4t-\gamma^2))\Big)^2$$

The demand addressed to the airport is:

$$D_A^D = \frac{2(3(c_T - f) + 5t) - 3\delta(c_{SAF} - t)}{3(8t - \gamma^2)}$$

We compute the airport's, airlines, and the train operator's profits:

$$\pi_A^D = \pi_A^* + \delta\Big(\frac{\delta(3c_{SAF}(28t - 3\gamma^2) + 6tc_{SAF}(4t - \gamma^2) + t^2(20t - \gamma^2))}{48(8t - \gamma^2)}$$

$$-\frac{(3(c_T - f) + 5t)(c_{SAF} - t)}{3(8t - \gamma^2)}\Big)$$

$$\pi_1^D = \pi_2^D = 0$$

$$\pi_3^D = \frac{(t(14t - 3(2(c_T - f) + \gamma^2 - 3\delta(c_{SAF} - t)))^2}{9t(8t - \gamma^2)^2}$$