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 considering implementing 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; they end up being excluded from the market. Instead, if a regulator authorizes discriminatory aeronautical charges, airlines may 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, then discriminatory charges increase the market share of air transportation. Thus, using a blend may prevent losing passengers to 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, 184 states and 57 organizations adopted the goal of reaching net-zero carbon (CO2) emissions in aviation by 2050. According to the ICAO (2019b), this sector currently accounts for only about 2% of global CO2 emissions. Nevertheless, demand is expected to grow by 4.3% each year over the next 20 years, increasing the sector's net contribution to climate change (ICAO, 2019a). Reducing CO2 emissions from aviation is crucial to mitigate climate change. This goal calls for policies supporting less-CO2-intensive technologies but also leaves room for decentralized approaches. Namely, a system of differentiated airport charges based on airlines' environmental performance. This latter scheme may provide incentives for airlines to reduce their emissions by switching to sustainable fuels or more radical technologies.[1] Such an approach is already being studied by Schiphol, Heathrow, and airports from the Swedavia AB group (EASA, 2022b). According to the IATA (2019), some airports already offer reduced charges to certain airlines.[2] Article 15 of the 1944 Chicago Convention forbids the use of discriminatory airport charges because it distorts competition.[3] In this context, one might wonder about the incentives to authorize differentiated charges if the discrimination is based on environmental performance. This paper studies the effects of such a decentralized approach.

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. In 2021, the ICAO launched the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to reach this goal. This scheme has three phases; during the first two, participation is voluntary, whereas, from 2027 on, participation will be "compulsory".[4] Airlines may offset their CO2 emissions with sustainable aviation fuels (SAFs) or other technological improvements.[5] The European Commission released in 2021 a set of legislative proposals known as the "Fit for 55" package aimed at reducing greenhouse gas (GHG) emissions by 55% by 2030 (from the 1990 baseline level). These proposals cover different sectors, such as aviation, and propose a revision

[1] For instance, new propulsion systems relying on hydrogen or electricity.

[2] Low-cost carriers often obtain reduced charges (Malavolti and Marty, 2019).

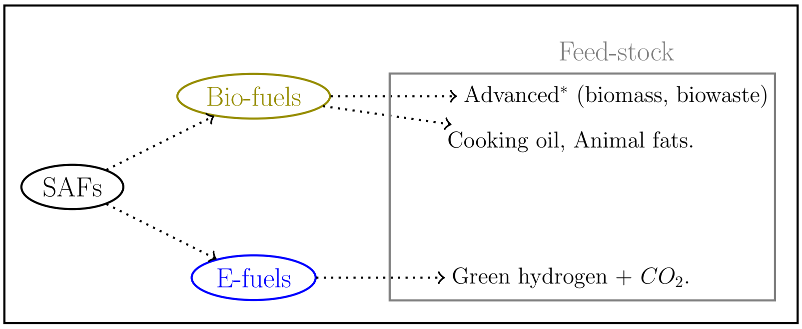
[3] The Chicago Convention establishes the ground rules for international aviation: airspace use, aircraft registration, and safety. It also exempts jet fuel from taxes.

[4] 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).

[5] Another alternative is to purchase carbon credits.

of existing policies such as the Renewable Energy Directive (RED II), the Energy Tax Directive (ETD), and the Emissions Trading System (ETS). The revised RED II advocates for a more ambitious 2030 target for fossil energy replacement with biofuels (1.75% to 2.2%) and e-fuels (0% to 2.6%). To reach this goal, the ReFuelEU Aviation proposal introduces a minimum share of drop-in SAFs (advanced biofuels and e-fuels see Figure 1) for all flights departing from European airports.[6]

Figure 1: SAFs considered in the "Fit for 55" package



* List in RED Annex IX part A

Drop-in SAFs have a high potential for emissions reduction as they are fully compatible with existing aircraft and fuel infrastructure. The combustion emissions are similar between fossil fuels and SAFs; thus, the added value of the latter depends on how sustainable their production pathway is (Mayeres et al., 2021).[7] So far, SAFs' uptake in aviation has been limited; this, in part, can be explained by a lack of policy incentives and the significant cost gap with respect to conventional jet fuel. For instance, the ICCT (2022) estimates that the cost gap between jet fuel kerosene and SAF from hydro-processed waste oils is at 0.24 EU per liter. Furthermore, today, SAFs' production capacity in the EU could only cover about 0.05% of the total EU aviation fuel demand (EASA, 2022a). A carbon price of 85 euros per tonne in 2030, combined with a carbon tax of 0.52 euros per liter on jet kerosene, could close the cost gap between jet kerosene and some SAFs, according to the ICCT (2022). Beyond governments, other public or private actors in the supply chain may be able to provide incentives for airlines to switch to SAFs. For instance, Schiphol, Heathrow, and airports from the Swedavia AB group are studying the possibility of implementing a system of differentiated airport charges based on environmental performance (EASA, 2022b). Today, discriminatory charges are forbidden under Article 15 of

[6]This applies to European Union (EU) and non-EU airlines.

[7]SAFs' production may compete with other sectors for feedstock (e.g., biomass for food and waste for heat).

the Chicago Convention. In the EU, the 2009 Airport Charges Directive (ACD) has reinforced this non-discrimination principle (Conti et al., 2019).[8] How far would a regulator authorize the use of discriminatory charges?

Depending on the origin-destination market, air transportation might face competition from other transportation modes, such as rail or road. Today, the cost of rail travel per kilometer in the EU is roughly three times that of air travel (OFS, 2021). Nevertheless, the EIB (2020) argues that consumers' growing environmental awareness might incite them to shift from planes to trains when offered the alternative. The empirical literature provides evidence that High-Speed Rail (HSR) decreases demand for air travel on competing short- to medium-haul routes (Friederiszick et al., 2009; Givoni et al., 2012; Dobruszkes et al., 2014; Wang et al., 2021). Specifically, air and rail competition seems to be strong when rail travel time is around 2h to 2h30. According to Givoni et al. (2012), HSR markets are those where the rail travel time is less than three hours. Dobruszkes et al. (2014) defines HSR services as high-speed lanes with trains traveling at a minimum of 250 km per hour. In terms of environmental performance, D'Alfonso et al. (2015, 2016) show that, despite rail's lower environmental footprint, the introduction of HSR may increase CO2 emissions. Indeed, there is a trade-off between two effects: mode substitution and traffic generation. Nevertheless, intermodal competition is welfare enhancing: it reduces the price of both plane and train tickets (Yang and Zhang, 2012). More broadly, intermodal competition incites airlines to modify the way they operate. For instance, Jiang and Zhang (2016) find that under modal competition, airlines tend to cover more fringe markets. Jiang et al. (2022) find that, conversely to intramodal competition, intermodal competition may reduce airports' and airlines' welfare-maximizing actions. For instance, they may decrease efforts to reduce delays. In the context of consumers' increasing environmental awareness, another strategy for airlines could be to move closer to rail's environmental performance by using a blend of drop-in SAF and kerosene. To our knowledge, intermodal competition when airlines use SAFs as a strategy to compete with rail has not been formalized in a theoretical model. This paper aims to fill this gap in the literature. Could the use of SAFs prevent airlines from losing passengers to rail?

Traditionally, aeronautical activities have been considered the main source of revenues for

[8] In fact, the ACD only applies to airports serving more than five million passengers per year, thus small and medium-scale airports do enjoy a certain degree of freedom regarding their charges level.

airports (Gillen, 2011). Nevertheless, commercial activities also represent an important and increasing source of revenue. For instance, in 2014, about 61% of Paris Airports' revenues came from commercial activities, while they only represented about 54% of total revenues in 2009 (Malavolti and Marty, 2019). Thus, airports earn revenues from both aeronautical and commercial activities; they are two-sided platforms where passengers and shops meet (Gillen, 2011; Ivaldi et al., 2015; Malavolti, 2016; Flores-Fillol et al., 2018; Malavolti and Marty, 2019). Armstrong (2006) and Rochet and Tirole (2006) argue that platforms are two-sided when consumers on one side generate externalities on the other side. These network effects may provide incentives for firms to distort prices across the sides. For instance, airports may try to attract more passengers through reduced aeronautical charges and compensate for the lost revenues with higher commercial fees.[9] In the context of modal competition, it is important to account for this particular feature of airports, as competition between transportation modes can impact revenues from aeronautical activities. For instance, the increased competitive pressure might reduce the airport's ability to exert market power on that side of the platform. Drop-in SAFs allow airlines to move closer to rail's environmental performance. The impact of this strategy on the airport's revenues is less clear. On the one hand, it may increase the total number of passengers visiting the airport. On the other hand, if aeronautical charges are too high, as SAFs are more costly than kerosene, airlines may choose to cease operations at that airport. This could decrease the total number of passengers and thus the airports' revenues. How would differentiated aeronautical charges impact airports' management of aeronautical and commercial activities?

We consider an origin-destination (OD) market where consumers have the choice between different transportation modes. Our aim is to provide a global picture of passengers' choices when they have access to different transportation offers. Specifically, consumers can fly or take the train in our setup. Two airlines operate from a monopolist airport platform at a two-part uniform aeronautical fee.[10] They compete in prices with one rail operator. This configuration is in line with reality. For instance, in the Toulouse-Paris market, a low-cost (Easyjet) and a full-service carrier (Air France) compete with France's national state-owned railway (the

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

[10] For instance, at Charles-de-Gaulle (CDG) and Paris-Orly airports, the landing fee combines a fixed and a variable part which depends on the aircraft's maximum take-off weight.

SNCF).[11] Other examples are the Biarritz-Paris, Montpellier-Paris and Pau-Paris markets all served simultaneously by Transavia, Air France, and the SNCF.[12] Furthermore, considering more than one airline at a time allows us to assess how a change in regulation influences airlines' choices (e.g., prices and output) when facing both inter- and intramodal competition. We build on Salop (1979) and consider that the firms are symmetrically located along a circle of unit length; their locations aggregate a set of hedonic characteristics. There is a unit mass of passengers located along the circle whose locations describe their ideal form of travel.[13] Buying a ticket from a firm offering a different product than the passenger's preferred one creates a disutility proportional to distance in the product space. We build on Hoernig (2015) and consider that airlines can use a drop-in SAF and kerosene blend and move closer to the train's product. This strategy allows for emissions reduction and leads to more differentiated airlines, but it increases the operational costs of the airline using blended fuel. We assume that when one airline uses the blend, the other firms cannot change their offer in the short term.[14] Namely, their locations remain unchanged along the circle.

We find that the two transportation modes coexist in markets where their cost difference is strictly smaller than the passenger's disutility associated with not traveling with their preferred transportation mode. When a large share of passengers pays for commercial activities, the airport reduces the per-unit aeronautical charge. This discount is used to attract passengers; higher rents, as well as a higher lump-sum fee, compensate for the revenue losses. This relationship between aeronautical and commercial charges is in line with the literature (Gillen, 2011; Ivaldi et al., 2015; Malavolti, 2016; Flores-Fillol et al., 2018; Malavolti and Marty, 2019). We remark that the airport operates in this market only when passengers' disutility from not traveling with their preferred means of transportation is large with respect to the share of passengers consuming services at the airport. In such a case, the lump-sum fee and the rent set by the airport increase with the operational cost of rail. In what concerns the per-unit airport charge, the latter only increases with the operational cost of rail for high values of the passengers' disutility. Thus, when passengers strongly dislike buying other tickets than their

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

[12] Air France serves the Biarritz-Paris and Pau-Paris markets through its Air France Hop brand, which was created to compete with low-cost carriers. That is, its operational costs are close to those of low-cost carriers.

[13] 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.

[14] For example, changing departure times may cause conflicts with other train lines or flights.

preferred ones, under intermodal competition, 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. Under the current regulation (i.e., uniform charges), if passengers' reservation price is such that we always have a covered market, the airport always excludes the blend-using airline from the market. We conclude that, at equilibrium, unilateral adoption of environmentally friendly jet fuel is not possible with uniform tariffs. Indeed, the current regulation limits incentives to reduce CO2 emissions if airlines anticipate market exclusion. Thus, like D'Alfonso et al. (2015, 2016) air-rail competition has a negative effect on the environment. However, in our paper, this negative effect is related to the lack of incentives to switch to less polluting fuels rather than a trade-off between modal substitution and increased traffic. When a regulator authorizes differentiated aeronautical charges, airlines are indifferent about using the blend. Indeed, although the blend gives access to reduced aeronautical charges, airlines always make zero profits. This is a direct consequence of the airport's monopoly situation, which allows it to extract all the airlines' profits. Several studies in the literature (Starkie, 2002; Oum and Fu, 2008) have highlighted the complex relationship between aeronautical charge size and competition between airports. For instance, Haskel et al. (2013) find that competition between independent airports in the same catchment area results in lower aeronautical charges. Nevertheless, this increased competition does not necessarily lead to lower ticket prices. Its findings have been reinforced with empirical evidence from Europe by Bel and Fageda (2010) and Bottasso et al. (2017). However, using data from the United States, Van Dender (2007) and Bilotkach et al. (2012) find a non-statistically significant relationship. In our setup, additional incentives to ensure that the blend-using airline makes strictly positive profits could lead to the unilateral adoption of a blend. Thus, authorizing differentiated charges does provide incentives to use SAFs, compared to a uniform charges situation. Nevertheless, Lin (2022) studies the implementation of differentiated airport charges in an international network and argues that uniform charges are always welfare-enhancing, regardless of the degree of airport congestion and airline differentiation. Notice that, with differentiated charges, the market share of air transportation may be lower than in the benchmark. This is the case when the additional costs associated with using a blend are strictly higher than the passenger's disutility associated with not traveling with their preferred transportation mode. In such a case, using a blend is not a good strategy for airlines to avoid losing passengers to the rail in the context of increasing environmental concerns. Otherwise, if the costs associated with using a blend are lower, the blend will increase the number of passengers visiting the airport.

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.

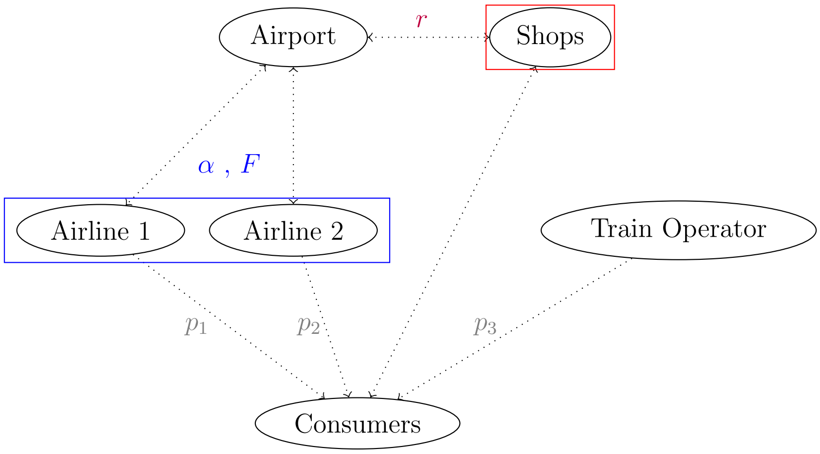
2 The Model

We consider an OD market where consumers have the choice between different transportation modes. Our aim is to provide a global picture of passengers' choices when they have access to different transportation offers. Thus, we consider all the transport supply in a given market. This approach allows for general policy recommendations (taxes, subsidies, and tariff designs) that consider the global supply. Specifically, in our model, consumers can fly or take the train (Figure 2). According to Dobruszkes et al. (2014), intermodal competition is strong in markets where the rail travel time is less than 3 hours. 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 that 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 allow us to assess how a regulation change would influence airlines' choices (e.g., prices and output) when facing both inter- and intramodal competition. Furthermore, this latter situation is in line with reality. 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).[15] 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, Montpellier-Paris,

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

and Paris-Pau markets served simultaneously by Air France, the SNCF, and Transavia.[16]

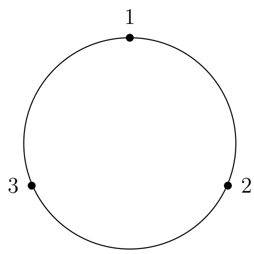
Figure 2: Organization of the market



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.

Figure 3: Product Space



2.1.1 Rail Travel

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

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.

[16]Air France serves the Biarritz-Paris and Paris-Pau markets through its Air France Hop brand which was created to compete with low-cost carriers. That is its operational costs are close to those of low-cost carriers.

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

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

and a fixed lump-sum fee:

$$F_1 = F_2 = F$$

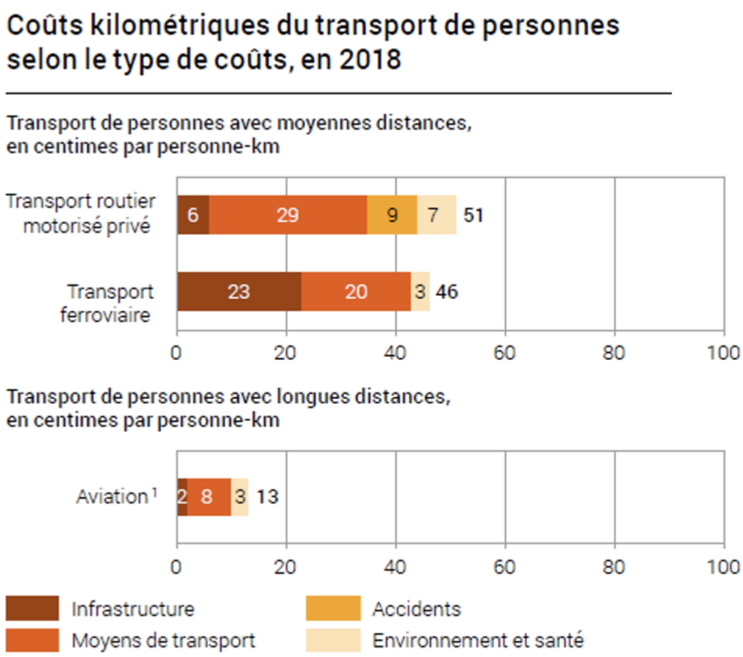
Figure 4: Landing charges at Paris' Airports

Aircraft landing fees excluding noise level coefficient	
Price per landing (€ excluding VAT)	304.38 + 4.251 x t where t equals MTOW in tons

Source: Paris Airports (2022)

For instance, at CDG and Paris Orly airports, the landing fee combines a fixed and a variable part proportional to the aircraft's maximum take-off weight (see Figure 4).

Figure 5: Air vs Rail transport costs for the sector per passenger per kilometer (CHF).



Source: OFS (2021)

Today, rail's operational and fixed costs are larger than those of air transport: $c_T - \alpha > 0$

(Figure 5). 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 airport passengers shop or use other paying facilities (e.g., parking or buses). 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:

$$\frac{\partial C(.)}{\partial D_A} < 0$$

the operational costs of airports are larger than rail's: $c_T > f$ (Figure 5).

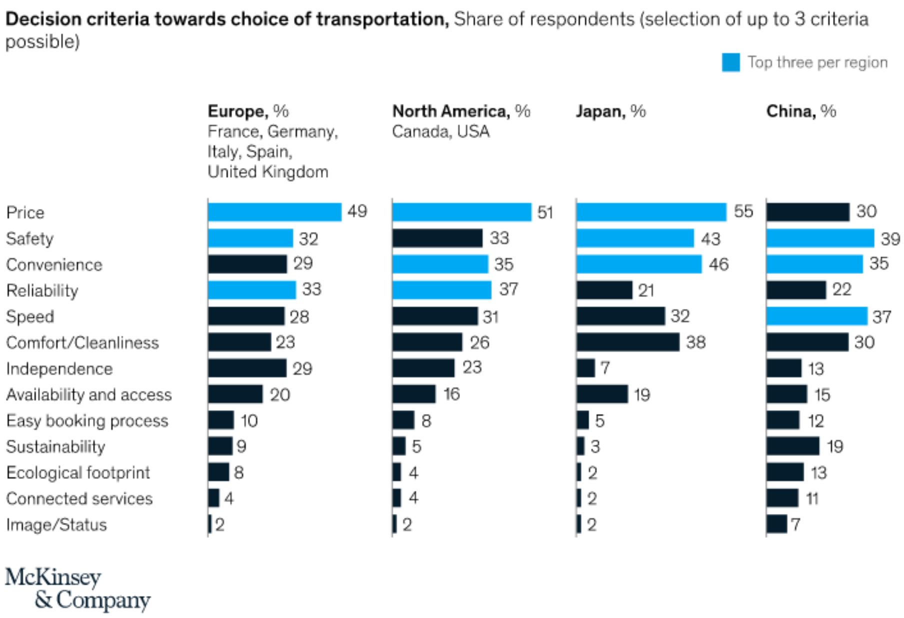
Assumption 1. $c_T > \alpha + f$ *the operational costs of air are larger than rail travel.*

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 6).[17]

[17] For instance, Koech et al. (2023) find that when consumers participate in a frequent flyer program, they tend to stick with a certain airline brand even if it is perceived as inferior in terms of quality.

Figure 6: Passengers' key criteria when selecting a transportation model



Source: McKinsey & Company (2022)

The net utility of a passenger traveling with a firm k is equal to:

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

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

We assume that all passengers are willing to 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 comfort, and $\beta_1 \neq \beta_2$ could be related to quality preferences (e.g. low-cost carrier vs 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.

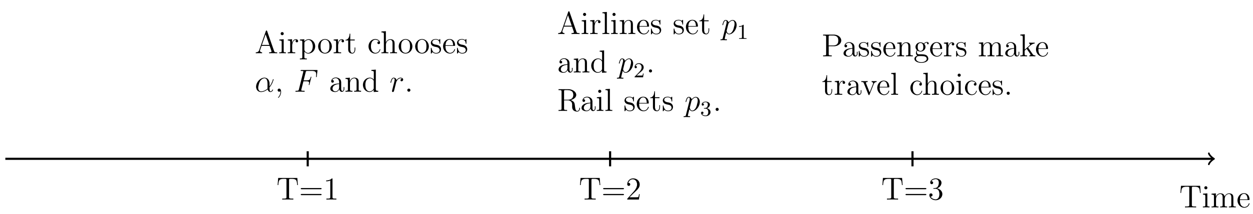
- $T = 3$: Demand realises.

Our equilibrium concept is a sub-game perfect 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 7).

Figure 7: Decision Tree



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 rail are active in the market.*

Hence, passengers have the choice between traveling by air or rail. Otherwise, when $\alpha \leq \underline{c}$ (respectively. $\bar{c} \geq \alpha$) only air (respectively. rail) travel is available for passengers.

Proof. See Appendix A.1. $\square$

Today rail operational costs are about three times larger than air $\bar{c} > c_T > \alpha > 0$.[18] 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 means of transportation: $t > \frac{5t}{6} > c_T - \alpha$. Otherwise, when $\frac{5t}{6} \leq c_T - \alpha$ passengers can only travel by plane. Nevertheless, air travel operational costs might increase as a result of the different environmental policies aimed at decreasing 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:

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

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, 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. Else, airlines might be tempted to switch to another airport to avoid making null profits.

[18]The OFS (2021) estimates a cost per passenger per kilometer at 0.46 CHF for rail and 0.13 for air transport.

Lemma 2. *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.*

Proof. See Appendix A.2. □

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. Indeed, the airport uses this discount as a means to attract passengers and compensates for this reduced fee with a higher rent and lump-sum fee.

Lemma 3. *The demand addressed to the airport is positive when passengers' disutility from not traveling with their preferred means of transportation is large with respect to the share of passengers consuming at the airport:* $t > \hat{t} = \frac{\gamma^2}{8}$*. Else, passengers travel only by train.*

Proof. See Appendix A.3. □

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.

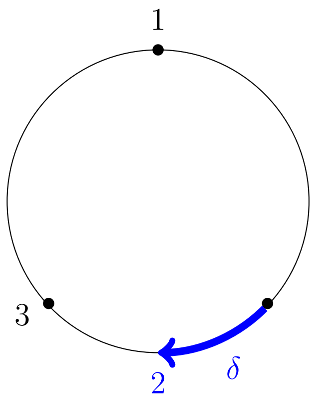
4 Innovation

We now assume that airline $k = 2$ can operate using a drop-in SAF and kerosene blend. 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 jet fuel kerosene and SAF from hydro-processed waste oils is 0.24 EU per liter. Here δ represents the percentage of drop-in SAFs that can be safely blended with jet fuel kerosene.[19] We build on Hoernig (2015) and consider that the airline using the blend moves closer to the train operator's product. 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 at a distance $\frac{1}{3} + \delta$ from airline 1. 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.[20]

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

Airline 2 becomes a closer substitute to rail travel and we have more differentiated airlines in the market (see Figure 8). 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.

Figure 8: 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 $k+1$:

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

[19] 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 synthetic kerosene.

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

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 4. *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 rail are active in the market. Hence, passengers have the choice between traveling by air or rail. Otherwise, when $\alpha \leq \underline{c}^u$ (respectively. $\bar{c}^u \geq \alpha$) 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.4. □

When airline 2 uses a blend, the threshold value of the air operational costs at which consumers no longer fly is higher than in the benchmark ($\bar{c} < \bar{c}^u$). Thus, airline 1 continues to compete with rail even when airline 2 is excluded from the market ($c^u < \bar{c} < \bar{c}^u$). 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 the demand for airline 2 is lower. Also, notice that the threshold value of the operational cost difference such that consumers no longer take the train is smaller ($\underline{c}^u < \underline{c}$). This implies that rail is more easily excluded from the market than in our benchmark case and loses passengers to airline 1. This latter situation implies a larger net level of emissions. Depending on the magnitude of the additional costs associated with using a blend δc_{SAF}, in comparison 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. That is when $\delta c_{SAF} > t(5 - 3\delta)$, i.e., when the operational costs of airline 1 are such that $\alpha < c^u < \underline{c}^u$. This implies that, depending on the size of the extra costs from using a blend, airline 2 may only be able to operate in markets without intermodal competition. This raises concerns about the lack of incentives to use an environmentally friendly blend when other airlines in the same market continue to use a less expensive but more polluting fuel. If it is too costly to use a blend, then 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:

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

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

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

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.

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):

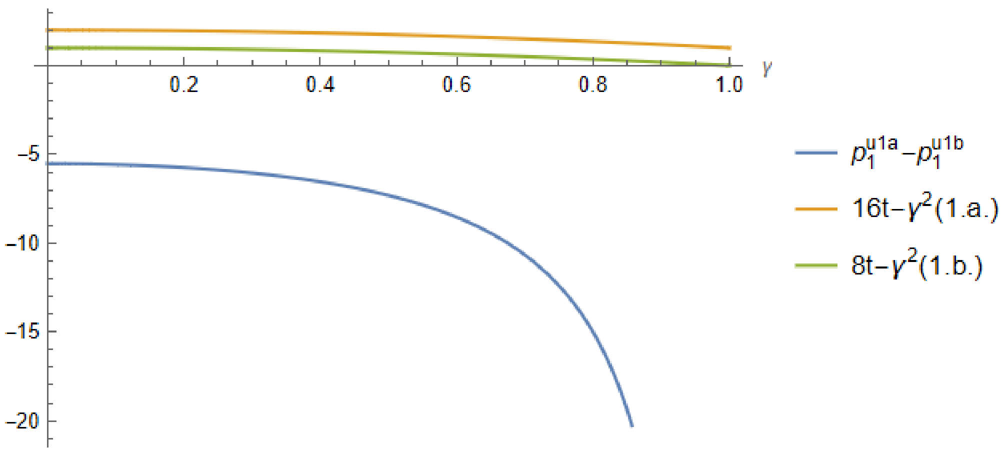
Table 1: Airlines' payoffs under uniform tariffs

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

To determine what the airport will do at the equilibrium we need to compare its payoffs given the different cases. When airline 2 is excluded from the market; then the percentage of drop-in SAFs blended is 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, i.e. when demand directed at airline 1 is positive (see Figure 9).

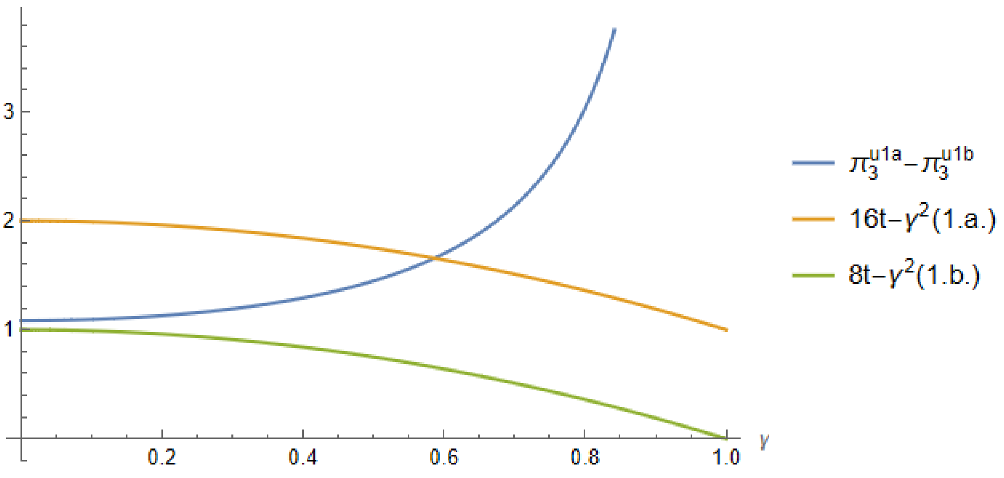
Figure 9: Airline 1's equilibrium prices case 1.a. and 1.b.



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 10). 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.

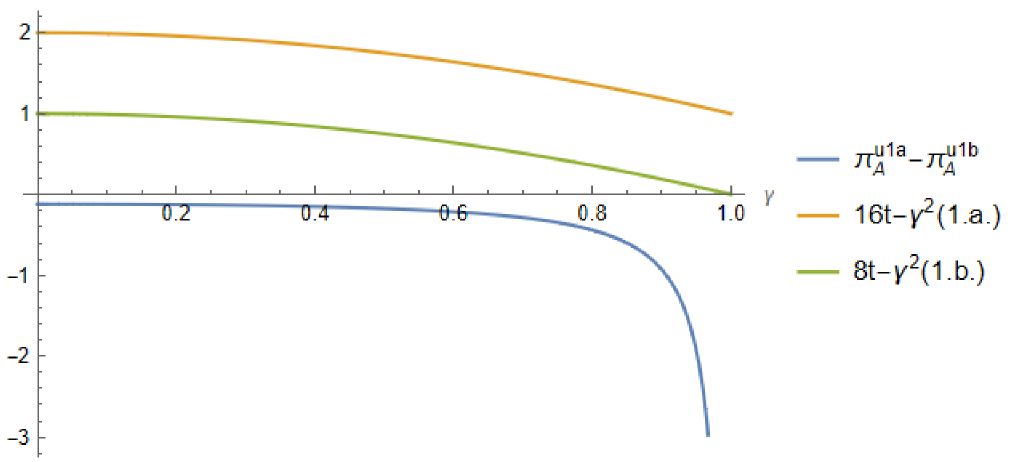
Indeed, now the firms have the same competitor on both sides of the circle.

Figure 10: Train operator equilibrium profits cases 1.a. and 1.b.



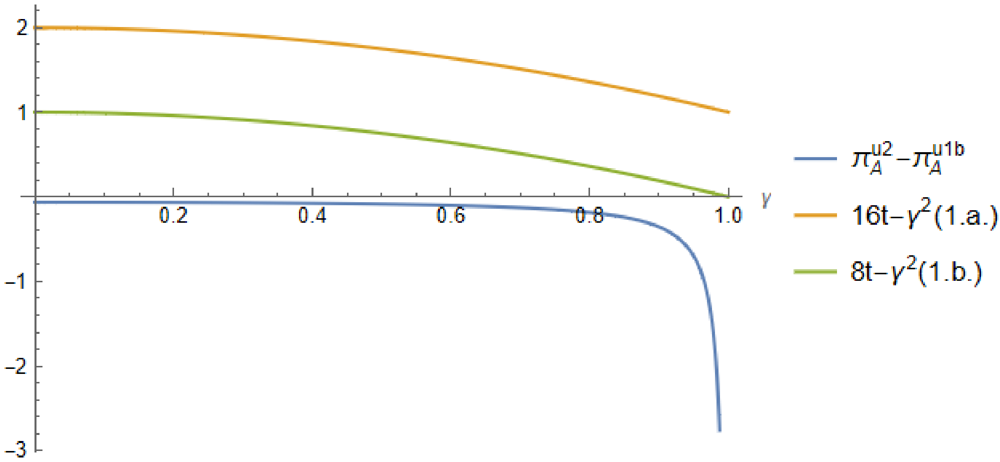
The airport always prefers to have a covered market when the condition $8t > \gamma^2$ is met (see Figure 11). Assumption 1 implies that the reservation price in this market is high enough for all passengers to always buy one ticket. So when airline 2 is excluded from the market, passengers shift to 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 11: Airport equilibrium profits cases 1.a. and 1.b.



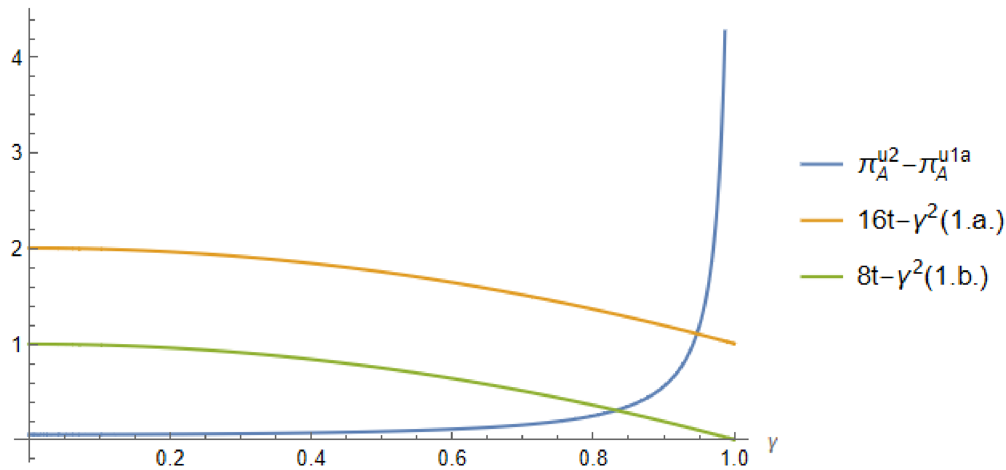
Provided that we have always a covered market, as long as the condition $8t > \gamma^2$ is met, then the airport prefers to serve only airline 1 rather than serving both airlines when one of them chooses to use a SAFs and jet fuel kerosene blend (see Figure 12).

Figure 12: 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 13). 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 13: 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 value is such that the market is always covered, the demand addressed to the airport is larger if it excludes airline 2: $D_A^{u1b} > D_A^{u2}$ as $-33\delta c_{SAF} < t(10-9\delta)$ (recall that $\delta \in [0; \frac{1}{3}]$). Moreover, by excluding airline 2, the airport reduces the intermodal 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.5. □

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 differentiated aeronautical charges based on environmental performance as a real possibility (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 14). 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 14: 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 5. *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.6. □

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 6) 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:

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

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

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

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

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 is indifferent between using or not a blend.*

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.7. □

Notice that if an extra monetary incentive $\epsilon \to 0$ is given to airline 2, then the latter will switch to an environmentally friendly fuel. 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 larger than the disutility $c_{SAF} > t$, then using a SAF and kerosene blend is not a good strategy for air transport to avoid losing passengers to rail in the context of passengers' increasing environmental concern.

Else, if the costs are smaller, then the blend will increase the total number of passengers visiting the airport.

5 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 latter is excluded from the market at the equilibrium. This limits airlines' incentives to reduce their CO2 emissions. Indeed, no airline will be willing to use a blend if they anticipate market exclusion. In fact, 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

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

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. If provided with extra incentives like a lump-sum subsidy or a direct payment from the airport, such that the blend-using airline makes strictly positive profits, then the latter will use the less polluting fuel. Thus, a decentralized approach supporting the adoption of SAFs could contribute to reducing emissions from air transport. Nevertheless, discriminatory charges may reduce the market share of air transportation compared to the benchmark. That is when the additional costs associated to the blend are high compared to passengers' disutility associated with not traveling with their preferred transportation mode. In such a case, using a blend would not be a good strategy to avoid losing passengers to rail in the context of passengers' increasing environmental concerns. Else, when the costs of using a blend are smaller than passengers' disutility, the blend increases the total number of passengers visiting the airport.

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.

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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:

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

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

and profits:

$$\pi_1(\alpha)^* = \pi_2(\alpha)^* = \frac{(3(c_T - \alpha) + 5t)^2}{225t} - F$$

$$\pi_3(\alpha)^* = \frac{(6(\alpha - c_T) + 5t)^2}{225t}$$

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:

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

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

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

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, the train operator and shops' profits:

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

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

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

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

Consumer surplus and social welfare are respectively:

$$CS = \beta + \frac{24t(3t(c_T - f)^2 - f(34t + 3\gamma^2) + t(77t + 62c_T)) + t\gamma^2(47\gamma^2 - 632t)}{36(8t - \gamma^2)^2} - \frac{c_T\gamma^2(14t - \gamma^2)}{(8t - \gamma^2)^2}$$

$$SW = \beta - \frac{11t}{36} - c_T + \frac{2t(3(c_T - f) + 5t)^2}{3(8t - \gamma^2)^2} + \frac{(3(c_T - f) + 5t)(3(c_T - f + \gamma) + t)}{9(8t - \gamma^2)}$$

A.3 Proof of Lemma 3

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.4 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

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

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:

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

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

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

and profits:

$$\pi_1(\alpha)^u = \frac{(3(c_T - \alpha + \delta(c_{SAF} + t)) + 5t)^2}{225t} - F$$

$$\pi_2(\alpha)^u = \frac{(3(c_T - \alpha - 2\delta c_{SAF}) + 5t)^2}{225t} - F$$

$$\pi_3(\alpha)^u = \frac{(6(\alpha - c_T) + 3\delta(c_{SAF} - t) + 5t)^2}{225t}$$

A.5 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.5.1 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.4 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:

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

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, the train operator and shops' profits:

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

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

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

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

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 $\hat{x_{1,3}}$ the consumer indifferent between traveling with airline 1 or taking the train:

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

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

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

The demand functions are:

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

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, the train operator and shops' profits:

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

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

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

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

A.5.2 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:

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

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

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

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, the train operator and shops' profits:

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

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

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

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

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

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

A.6 Proof of Lemma 5

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:

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

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

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

and profits:

$$\pi_1(\alpha_1,\alpha_2)^D = \frac{(3(c_T - 2\alpha_1 + \alpha_2 + \delta(c_{SAF} + t)) + 5t)^2}{225t} - F_1$$

$$\pi_2(\alpha_1,\alpha_2)^D = \frac{(3(c_T + \alpha_1 - 2\alpha_2 - 2\delta c_{SAF}) + 5t)^2}{225t} - F_2$$

$$\pi_3(\alpha_1,\alpha_2)^D = \frac{(3(\alpha_1 + \alpha_2 - 2c_T + \delta(c_{SAF} - t) + 5t)^2}{225t}$$

A.7 Proof of Proposition 2

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

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

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

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

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:

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

The first order conditions give:

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

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

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

We can plug equation 11 into equations 9 and 10:

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

$$\underbrace{\frac{1}{5t}(p_1(\alpha_1,\alpha_2)-f)}_{>0}+\underbrace{\frac{-2}{5t}(p_2(\alpha_1,\alpha_2)-f-\delta c_{SAF})}_{<0} + \underbrace{D_1(\alpha_1,\alpha_2)\Big(\frac{2t-\gamma^2}{10t}\Big)}_{\text{if} \quad 2t>\gamma^2}+\underbrace{D_2(\alpha_1,\alpha_2)\Big(\frac{6t-\gamma^2}{10t}\Big)}_{\text{if} \quad 6t>\gamma^2}=0 \quad (13)$$

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, the train operator and shops' profits:

$$\pi_A^D = \pi_A^* + \delta\Big(\frac{\delta(3c_{SAF}(28t - 3\gamma^2) + 6tc_{SAF}(4t - \gamma^2) + t^2(20t - \gamma^2))}{48(8t - \gamma^2)} - \frac{(3(c_T - f) + 5t)(c_{SAF} - t)}{3(8t - \gamma^2)}\Big)$$

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

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

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