Master’s Degree in Data Science and Economics

Environmental Charges and International Aviation: Leveraging Airline Supply Elasticity to Mitigate CO2 Emissions in Alignment with ICAO 2050 Target

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1 Introduction

In slightly over a century since the first take off of a civil flight, the aviation sector has experienced rapid expansion and has become an indispensable and essential element of modern society.
According to the 6^{th} Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [9], in 2019, the transport sector contributed 8.7 gigatons of CO2-equivalent (GtCO2-eq) in direct greenhouse gas (GHG) emissions, a substantial increase from the 5.0 GtCO2-eq recorded in 1990. These emissions constituted 23% of the global CO2 emissions linked to energy production. Notably, road vehicles accounted for the largest share, representing 70% of direct transport emissions. Meanwhile, rail, shipping, and aviation were responsible for 1%, 11%, and 12% of these emissions, respectively. While it may seem that aviation has a comparatively smaller impact with respect to road transportation, it is crucial to recognize that the aviation industry is one of the fastest-growing sectors within the transportation domain.

In the absence of policy measures, this growth is likely to persist in the future. This rapid expansion poses a significant challenge in achieving the ambitious goal of limiting the temperature increase to a maximum of 1.5-2 Celsius degrees, as outlined in the Paris Agreement [17]. Hence, it is of great importance to contemplate the present and potential future impacts of the aviation industry emissions on the atmosphere. The sector's growth trajectory demands immediate attention and action. As per the Committee on Aviation Environmental Protection (CAEP)/12[1], prior to the onset of the COVID-19 pandemic, the global Revenue Passenger Kilometres (RPKs)[2], were experiencing an annual growth rate of 4.2% worldwide, encompassing both domestic and international flights.
However, the emergence of the COVID-19 pandemic resulted in a significant downturn in passenger traffic demand in 2020, estimating a reduction of approximately 68% in

[1]The Committee on Aviation Environmental Protection (CAEP) is a technical committee of the ICAO Council established in 1983. CAEP assists the Council in formulating new policies and adopting new Standards and Recommended Practices (SARPs) related to aircraft noise and emissions, and more generally to aviation environmental assessments.
[2]RPKs is a metric for air transport demand, calculated as the product of the number of revenue passengers and the total distance traveled.

global RPKs. Consequently, the formulation of new RPKs forecasts must account for the uncertainties arising from the pandemic's short and long-term impacts on the global economy. To address this, CAEP developed three distinct COVID-19 traffic demand forecast scenarios to represent a plausible range of potential recoveries for the aviation industry. In the immediate future, these recovery projections indicate that global traffic demand is expected to return to 2019 levels by 2023, 2024, and 2027 for the high, mid, and low scenarios, respectively. Considering the mid scenario, spanning the period from 2024 to 2050, RPKs are projected to grow at an annual average rate of 3.6% for global demand, in accordance with the International Civil Aviation Organization (ICAO)[3] Environmental Report of 2022 [11].

Growth in air traffic does not correspond to a proportional growth in emissions. Significant advancements in technology and operational efficiencies, led to an 80% improvement in fuel efficiency compared to air transport operations of the past half-century. However, this progress has been overshadowed by a substantial increase in the number of passengers. According to ICAO, the number of passengers carried during the same period has surged five fold.

The substantial external costs associated with aviation, particularly regarding climate change, have driven the implementation of policies aimed at elevating the cost of air travel to mitigate the anticipated long-term growth in air traffic. As an example, flights within the European Economic Area have been integrated into the European Trading System (EU ETS) since 2013. Additionally, several nations have introduced various flight ticket tax schemes. These flight ticket taxes result in increased expenses for airlines, which, in turn, are expected to lead to higher ticket fares as airlines pass on a portion of the added costs to passengers. Consequently, the increased costs for airlines and/or the rise in ticket fares will induce a reduction in supply and emissions.

[3] ICAO is the United Nations Agency for Civil Aviation. Its primary mission is to fulfill the role of a global forum for States to engage in matters concerning international civil aviation.
Its mandate encompasses the development of policies and standards promoting and maintaining the safety, security, efficiency, and sustainability, conducting compliance audits and in-depth studies and analyses, providing valuable assistance, and fostering the growth and capability of the aviation industry through various collaborative activities involving its Member States and stakeholders. It serves as a platform for nations to come together, exchange knowledge, and collectively address challenges in the aviation sector.

In 2016, ICAO launched a new set of measures with the goal of reaching Carbon Neutral Growth from 2020 (CNG2020), that aims at keeping emission at 85% of 2019 level and a Long-term global aspirational goal of net-zero carbon emissions by 2050. The set of measures includes: new aircraft technologies, operational improvements, utilization of Sustainable Aviation Fuels (SAF) and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the first global market-based mechanism to harmonize all environmental policies in the aviation sector. CORSIA is meant to compensate for the quantity of CO2 emissions that cannot be curtailed through the other solutions. technological advancements, operational enhancements, and SAF. This compensation is achieved through emission offsetting units obtained by airline companies investing in carbon-offsetting projects. However, there’s a high risk that CORSIA is not stringent enough to pursue the net-zero emissions goal it aims at.

This research is mainly motivated by the urgency of taking compelling action against global warming. The task of mitigating climate change stands as one of the foremost challenges humanity currently confronts, and this endeavor is intended to be a small contribution to this critical cause, by attempting at reconciling the environmental impact of aviation with the escalating demand for air travel.

This thesis seeks to assess the feasibility of implementing an environmental charge as an alternative to CORSIA, increasing existing airport fees.
A key distinction between applying an environmental charge and a market mechanism to offset emissions such as CORSIA, is that a charge has the effect of directly reducing emissions at the source, rather than a subsequent compensation. In the former, CO2 emissions are prevented from entering the atmosphere, as opposed to the latter, where emissions are released and ”canceled” later through various CO2 offset programs.
Environmental levies are frequently employed as economic strategies to mitigate emissions. However, the pursuit of a global approach, which could prove to be the most effective means of minimizing spillover effects, remains unexplored.

The primary objective is to investigate the responsiveness of airline companies to changes in airport charges, examining the causal impact of increased overall airport fees on flight frequencies at the airline-route level, and subsequently, the resulting carbon emissions in the world's busiest airports.

The study draws upon a comprehensive dataset comprising airline-route pairs flying within the 87 largest airports worldwide, covering the years 2017 to 2022, with the exception of 2020, resulting in a total of 4,479 data points. This dataset encompasses information on airport charges and emission fees for two widely-used aircraft models, namely the Airbus A320 and Airbus A350-900 used respectively for medium and long-haul flights. Additionally, it incorporates data on the population and per capita income in the vicinity of both departure and destination airports, as well as the ownership structure of the airports.

Starting from an initial analysis of the data, it is noteworthy the substantial variation in charges across different countries and flight distances. Consequently, supply elasticity is estimated in four distinct scenarios, based on flight duration and the country of departure. These scenarios differ based on whether the flight is classified as medium or long-haul and whether it originates from an airport in Europe or North America as opposed to airports in other parts of the world.

In order to mitigate potential issues related to endogeneity concerning the impact of passenger traffic on charges, an instrumental variable is introduced into the model. The supply elasticity is then estimated using the Two-Stage Least Squares Model, while accounting for country and year fixed effects. The chosen instrumental variable is the airport ownership model, which can take various forms such as private ownership, public ownership, public-private partnerships, or a public infrastructure with the privatization only of terminals, a model observed in the United States. Typically, instances of airport privatization are associated with an increase in charges for airline companies.
The same regression model is also used to gauge the direct impact of charge increments on CO_2 emissions.

The main finding of this study reveals that, for airline companies operating medium-haul flights departing from European countries, the United States, or Canada, a 1% increase in charges leads to a reduction of departing seats by -0.83%. Consequently, this translates to a direct reduction in emissions by -1.39%.

However, in the other scenarios, the results lack statistical significance, possibly due to the substantial heterogeneity within the dataset. In fact, the second group of countries encompasses a wide range of geographical regions, including South America, the Middle East, and Asia, with very different charge ranges. Moreover, the varying flight durations for long-haul flights, spanning from 6 to 16 hours, give rise to markedly distinct emissions and charge structures.

Lastly, leveraging estimates for CORSIA offsets from realized by THE International Air Transport Association (IATA)[4], it's possible to calculate the necessary percentage by which airport charges should increase to achieve carbon neutrality in the aviation sector by 2050. To make a practical example, in 2024 the introduction of an environmental charge based on the supply elasticity of medium-haul flights departing from a European Union country should increase by 5.23 times the actual charge per passenger. For example, to fly from Stockholm - Arlanda Airport to Lisbon Airport an airline company should face a cost increment from 7.89€ to 41.68€ per passenger.

This cost increase can be very high for companies, but the revenue from the charge could be used to invest in research in new technologies and in Sustainable Aviation Fuels (SAF) or offsetting projects, accelerating the emissions reduction. Furthermore, the environmental charge is meant to gradually decrease during the years as airline companies adopt more sustainable solutions such as improved operational efficiency, adoption of SAF, etc.

[4]The International Air Transport Association is a global trade association comprising airlines worldwide. Established in 1945, IATA has been characterized as a cartel due to its role in not only establishing technical standards for airlines but also convening tariff conferences that historically facilitated discussions on pricing coordination. As of 2023, IATA represents 317 airlines, encompassing major carriers from more than 120 countries. These member airlines collectively account for roughly 82% of total available seat miles in air traffic, as of 2020.

The code used to obtain the results reported in this thesis can be found at this Github repository.
The structure of this thesis is organized as follows: Section 2 delves into the international framework of measures aimed at addressing CO2 emissions, with a specific focus on ICAO's CNG2020 goal and CORSIA. Section 3 addresses the existing literature regarding the implementation of charges within the domain of civil aviation. Section 4 provides an overview of the data utilized in this research. Sections 5 and 6 elaborate on the model employed for estimating supply elasticity and quantifying CO2 emissions reduction, respectively. Section 7 outlines the proposed approach for the application of the environmental charge. Finally, Section 8 is dedicated to concluding remarks and suggestions for future research enhancements.

2 International Measures to Counteract CO2 Emissions in Civil Aviation

Numerous efforts have already been undertaken, both by individual governments introducing environmental taxes and by International Organizations such as the European Union, which has implemented the European Emission Trading System (ETS), in the pursuit of addressing climate change.
The urgency of reducing greenhouse gasses to meet Paris Agreement's goal has led the International Civil Aviation Organization to take action with the scope of harmonizing these initiatives around its member states with a unique strategy for emission reduction. In 2016, ICAO's 39^{th} Session of Assembly has agreed on an aspirational goal for the international aviation sector: Carbon Neutral Growth from 2020 onwards (CNG2020). It consists in maintaining CO2 emissions produced by international aviation lower than 85% of the CO2 produced in 2019. While this objective marked an important step towards reducing the sector's environmental impact, it alone is not sufficient to align with the actions necessary to meet the goal established by the Paris Agreement. In order to effectively limit global temperature increase to less than 1.5-2 degrees Celsius by the year 2100, experts estimate that global CO2 emissions must be reduced to zero by around 2050. Consequently, ICAO added an even more ambitious goal of net-zero

carbon emissions by 2050.

In order to achieve these objectives ICAO has identified the following basket of strategies:

- Improved aircraft technology and standards efficiency.
- Air traffic management and operational improvements.
- 2% annual fuel efficiency improvement through 2050.
- Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

The synergy between the CO2 reduction measures is visually represented in Figure 1.

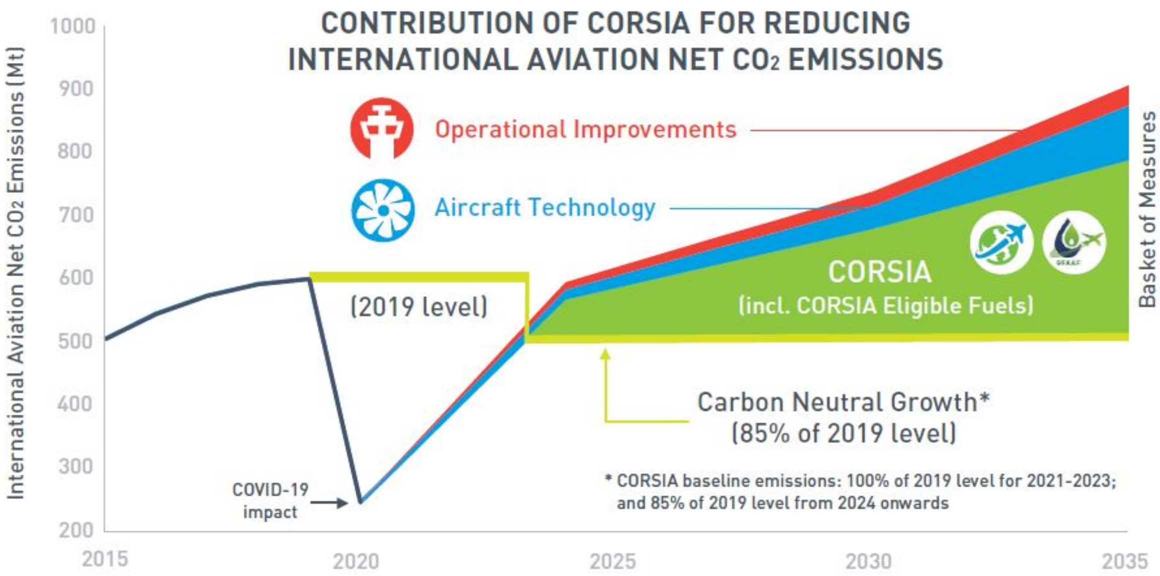

Figure 1: ICAO's projection of emissions reduction for the three phases of implementation of CNG2020.

2.1 CORSIA

CORSIA represents a global market-based measure with the intention to harmonize the fragmented approach of national or regional regulations already existing to deal with aviation emissions reduction of CNG2020. The key features of CORSIA are:

- It is active from 2021 to 2035 and is structured into three distinct phases:
  i) Pilot phase. From 2021 to 2023;

ii) First phase. From 2024 to 2027;

iii) Second phase. From 2027 to 2035.

- The pilot phase and the first phase are both voluntary stages, while the second phase is obligatory. The second mandatory phase applies to participating States, which are those with an individual share of international aviation activities in Revenue Ton Kilometers (RTKs) exceeding 0.5% of the total RTKs in the year 2018. It also includes States whose cumulative share in the list of States, ranked from the highest to the lowest amount of RTKs, reaches 90% of total RTKs. However, this does not apply to Least Developed Countries (LDCs), Small Island Developing States (SIDS), and Landlocked Developing Countries (LLDCs).

- CORSIA is applicable to all international flights that operate between participating States. Flights between a participating State and a non-participating State are exempted.

- Aircraft operators conducting flights between participating States are required to offset emissions that exceed the baseline emissions level. This baseline emissions level is determined by calculating the 85% of total emissions by flights covered by CORSIA in 2019. The emissions offsetting is achieved through a system of investments in sustainable projects to compensate the excessive emissions units. Emissions reduction projects are divided in emissions units on a per-tonne basis, where 1 Emissions Unit = 1 Tonne of CO_2.

- The offsetting is calculated at the end of the three-years period. For instances, during pilot phase the states have to communicate within 30th November 2024 the offsetting of airline companies for the period 2021-2023, and companies must comply with it by 31 January 2025 or 60 days after the State informs aeroplane operator(s) of total final offsetting requirements for the 2021-2023 period, whichever date comes later.

- The competent authority each year calculates the offsetting requirements of each airline operator through a specific equation based on the operator's growth factor for that year, the operator's emissions covered by CORSIA in that year and the growth factor[5].

- When this thesis is being redacted, 125 states have expressed their voluntary participation at CORSIA Program from 2024.

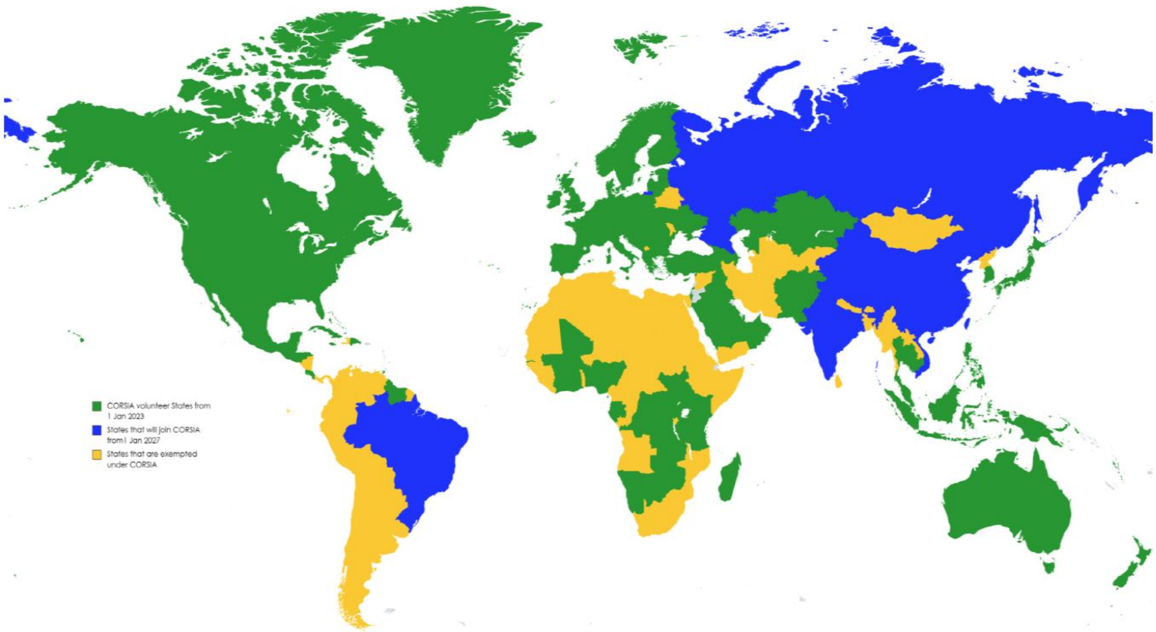

Figure 2: Map of the countries compulsory participating to the Second Phase of CORSIA, starting in 2027.

As CORSIA has been launched only since a couple of years there is still not enough data to be able to verify its actual impact on aviation emissions. However, waiting years to obtain the first research results is a serious risk of inaction during crucial years for counteracting climate change.

To have some anticipation of CORSIA's impact it's possible to draw insights from a sim-

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$$offset_t = [\%sectoral_t \times CO2_{operator_t} \times \nabla_{sector_t}] + [\%individual_t \times CO2_{operator_t} \times \nabla_{operator_t}]$$

The growth factor can be sectoral or individual and changes depending on the phase:

- Pilot phase (2021 - 2023)

$$\nabla_{sector_t} = \frac{C02_t - CO2_{2019}}{CO2_t}$$

- First and second phase (2024 - 2035)

$$\nabla_{sector_t} = \frac{C02_t - (0.85 \times CO2_{2019})}{CO2_t}$$

in literal terms can be translated into: the sector's growth factor from 2021 through 2023 is equal to the total emissions covered by CORSIA in the given year minus the total emissions covered by CORSIA in 2019 divided by the total emissions covered by CORSIA in the given year. The sector's growth factor from 2024 through 2035 is calculated in the same way except for the fact that the subtraction is only 85% of total emissions covered by CORSIA in 2019.

ilar market-based measure, the European Union Emission Trading System (EU ETS), which is active in the aviation sector since 2013 and has already undergone extensive scrutiny through numerous studies.

The EU ETS functions as a cap-and-trade system encompassing all sectors with significant CO2 emissions, including aviation. Each sector is allocated a specific quantity of free allowances based on their historical emissions. Once these free allowances are exhausted, companies have the option to acquire additional allowances from sectors that have a surplus. A cap is imposed on the issuance of emissions allowances, effectively limiting the total emissions permitted within the sector. In the case of aviation, this cap is set at 95% of the average emissions recorded between 2004 and 2006, adjusted for changes in applicability scope. The overall quantity of emissions allowances is finite and progressively reduced over time. The interplay between supply and demand dictates the price of these allowances within the ETS framework. Higher prices incentivize emissions reduction efforts, as operators seek to avoid the expense of purchasing additional allowances. EU ETS enforces a considerably more stringent emissions cap, (95% of the average emissions recorded between 2004 and 2006) compared to CORSIA (85% of the average emissions of 2019). The comparison between the two market-basket measures is addressed in the following section.

3 Literature Review

CE Delft [6] has compared the offset requirements under EU ETS and CORSIA framework for European Union Member countries plus Switzerland and United Kingdom for the period 2021-2035. In the case of CORSIA, 271 Mt of offsets are computed, whereas under EU ETS it amounts to 796 Mt, which is significantly higher compared to CORSIA. On top of that, not even the EU ETS threshold seem to be stringent enough to comply with the Paris Agreement, as stated by Cames et al., 2015 [18] :

"Full decarbonisation within only 30 years is rather unrealistic, stabilising emissions at 2020 levels (carbon neutral growth) is clearly not enough. To stay below 2°C, the target for aviation for 2030 should not exceed 39% of its 2005 emission levels".

A similar finding is confirmed by the paper of Fageda and Teixidò [7], in which they evaluate the impact of the EU carbon market on aviation emissions and supply. The authors find that emissions are reduced by 4.7% in the regulated routes relative to the counterfactual in the period 2010-2016 and up to 10.7% when restricting the sample to short-haul flights, showing that EU ETS, overall, helped to mitigate emission growth by 3 Mt CO_2 per year during the period analyzed. However, the emission reduction is far from meeting the target of the Paris Agreement.

Peeters et al. [15] also note that there's a prevalence of green narratives within the aviation industry, aiming to foster public perception of progress in emissions mitigation, even though the reality points towards continuous emission growth. Their findings indicate that the aviation industry has put forth numerous solutions to address the increasing emissions, only to later fade away and be replaced by new discussions on technology.

Simultaneously, the sector is driven by a focus on increasing volume growth, often at the cost of low profitability. This is evident in the deployment of budget-oriented marketing strategies, as investigated by Higham et al., 2022 [14], designed to stimulate demand growth, while rhetorically embracing forthcoming low-carbon technologies.

The available evidence suggests that without political intervention to enforce decarbonization, aviation emissions are expected to continue their rapid growth.

Furthermore, another issue is that CO_2 is not the only polluting substance produced by aviation. Aircraft release greenhouse gases directly into the upper troposphere and lower stratosphere altering the atmospheric composition. Carbon dioxide (CO_2) and water vapor (H_2O), alongside significant emissions such as nitric oxide (NO), nitrogen dioxide (NO_2) collectively referred to as NO_x, sulfur oxides (SO_x), and soot contribute to the formation of condensation trails; and may increase cirrus cloudiness, all of which contribute to climate change, as depicted by the IPCC, 1999 [10]. Assessing the climate impact of greenhouse gases and particles is more challenging compared to quantifying CO_2 emissions themselves. This is because carbon dioxide has a lengthy atmospheric presence, approximately around 100 years, whereas other gases like NO_x, SO_x, water vapor, and particles have shorter atmospheric lifetimes, remaining concentrated along flight routes, particularly in the northern mid-latitudes. These emissions can result in localized radiative forcing near flight routes for specific components like ozone and contrails, as opposed to emissions that have global ramifications. Due to the complexity of extending the offsetting to all GHG emitted in the atmosphere, CORSIA takes into account only C02, but the impact of aviation on climate change is even major.

In March 2022 CAEP released the Report on the Feasibility of a Long-Term Aspirational Goal for International Civil Aviation CO2 Emission Reductions [4], which focuses its analysis on the achievement of net-zero carbon emissions by 2050. In the summary of results and high-level observations of the official document is reported:

”While the scenarios show the potential for substantial CO2 reduction, none of the scenarios reach zero CO2 emissions through the use of in-sector measures (i.e. technology, operations, and fuels). This is due to the consideration of fuels' life cycle emissions and occurs despite a 100% replacement of conventional jet fuel with novel fuels e.g. Sustainable Aviation Fuel (SAF)-biomass, waste or atmospheric CO2 based fuels or hydrogen.”

Technology improvements and bio-fuels alone are not going to be enough to reach carbon neutrality in 2050, therefore an additional economical measure is still going to be necessary. It seems that the measures put in place by international organizations so far are not adequate to meet the ambitious goals they declare to pursue. An alternative to these kind of market-basket measures is an environmental charge, as already noted by the IPCC in its Special Report Aviation and the Global Atmosphere[10] in 1999:

”Environmental levies (charges and taxes) could be a means for reducing growth of aircraft emissions by further stimulating the development and use of more efficient aircraft and by reducing growth in demand for aviation transportation. Studies show that to be environmentally effective, levies would need to be addressed in an international

framework."

Research by Brueckner & Zhang, 2010 [3] examines the consequences of an emission charge that targets fuel price. The findings indicate that emissions charges will lead to higher ticket prices, a decrease in flight frequency, increased passenger load factors, and improved aircraft fuel efficiency.

Bernardo et al., 2022 [12] examine the causal impact of flight ticket taxes on airline supply and emissions at the airline-route level within the European Economic Area (European Union, Norway, Iceland and United Kingdom) and investigate its distributional effects between airlines and travellers, and within travellers. Their analysis reveals that ticket taxes lead to a 12% average reduction in the number of flights per airline-route compared to a hypothetical scenario, resulting in a consequential 14% decrease in carbon emissions. Moreover, given the relatively inelastic nature of passenger demand in response to price changes, a substantial portion of the tax burden is bore by passengers.

Research by Falk & Hangsten, 2019 [8] delves into the consequences of a flight departure tax implemented in Germany and Austria in 2011 on the passenger count for flights. The study encompasses data from 310 airports across 30 European countries spanning from 2008 to 2016. Through dynamic panel difference-in-differences estimations, it is observed that the flight tax results in a 9% reduction in the number of passengers in the year of its introduction and a 5% decrease in the subsequent year, predominantly in airports served by low-cost airlines.

A question that can raise is how a sector where there's usually high competition and low elasticity as aviation is going to respond to generalized higher costs. In cases where airlines do not transfer the increased burden to passengers, they will experience increased operating costs. In scenarios characterized by imperfect competition, these heightened costs will result in a reduction in airline supply, subsequently leading to decreased emissions. This effect stems from the charges raising airlines marginal costs, which, in turn, diminishes their profitability as indicated by Brander and Zhang, 1990 [2]. Conversely, as demand elasticity is usually low for flights, airlines can opt to pass the charge onto passengers through higher fares, that potentially will lead to a drop in demand. Reduced demand, in turn, contributes to a decrease in overall supply. Thus, irrespective of the rate at which costs are passed on, the charge is expected to result in reduced supply and emissions when comparing treated and control routes.

The extent to which airline companies can shift the cost burden to passengers varies depending on the category of travelers. Berry et al., 1996 [1], estimated the willingness to pay for both business travelers and tourists. It was found that tourists, being more price-sensitive, often opt for low-cost airline companies, whereas business travelers, who exhibit lower price elasticity, tend to prefer full-service carriers.

Network airlines typically operate hub-and-spoke networks, while low-cost carriers predominantly rely on point-to-point routes. Empirical analyses of the European aviation market have also revealed that low-cost airlines frequently choose less-traveled routes in comparison to network airlines. Moreover, factors such as route distance, competition, population density, and income levels at the endpoints of a route have varying impacts on the decisions regarding which routes to operate and at what capacity. These findings were highlighted in studies conducted by Calzada and Fageda, 2019 [5].

As a result, the introduction of a new environmental charge could affect low-cost and full-service airline companies in distinct ways. Nevertheless, the precise magnitude of this impact on these two airline models is not assessed within the scope of this thesis, but is left as a subject for future research.

As far as the scope of the research carried out during this thesis, there seems to be no other research that tried to expand the evaluation of the generalized impact of an environmental charge with data regarding different airports spreaded around the world. This thesis tries to move a first step towards filling this research gap.

4 Data

The data consists of 4,479 observations regarding 87 of the biggest airports around the world (list can be found in Table 5 in Appendix 1). The airports are divided in the following geographical areas:

- Europe: 31
- North America: 28
- Asia: 12
- Middle East: 9
- South America: 5
- Africa: 2

Russian airports have been excluded since the number of flights for 2021 and 2022 has significantly dropped after the aggression to Ukraine and would have counted as outlying values. Berlin-Tegel Airport is also dropped as it was closed permanently in 2020 and substituted by Berlin-Brandenburg Airport.

Data regarding airport charges, emissions and departures are collected from two different tools provided by RDC Aviation[6]:

- Apex-Schedules provides supply data at the route-airline level (seats, flight frequency, type of aircraft, primary airline company operating, emissions per seat per kilometer, total emissions per flight).
- Airport Charges provides detailed data on airport charges differentiating between passenger charges, infrastructure charges, government charges, parking charges, etc. The charges are calculated on round-trip flights and two hours parking of the airplane.

The data collected regards round-trip international flights with a minimum of weekly frequency. The routes chosen are of two types: medium-haul flights (from 3 to 6 hours) and long-haul flights (from 6 to 16 hours)[7]. This choice stems from the observation that medium and long-haul flights contribute significantly more with respect to short-haul and exhibit the lowest elasticity, as over longer distances, airplanes lack a direct sub-

[6]RDC Aviation is a global aviation data business. https://www.rdcaviation.com/

[7]Commercial flights are often categorized into long-, medium- or short-haul, although there is no international standard definition. The ones I adopted are the most common thresholds used by the aviation community.

stitute.

Domestic flights have been excluded from the analysis as ICAO's responsibility is limited to the coordination of international aviation, whereas domestic flights fall under the jurisdiction of individual states.

Fees vary from one airport to another and are contingent on various factors, including aircraft size, passenger count, parking duration, airport monopoly status, and more. To compute the charges, two most common aircraft models for medium-haul and long-haul flights have been selected: the Airbus A320, equipped with 180 seats, and the Airbus A350-900, equipped with 315 seats. The load factor is assumed to be 80, which means that on average the occupied seats are 80% of the total available. The data is collected for the years of 2017, 2018, 2019, 2021 and 2022. 2020 is not included in the research because it is the only year with a negative RPKs growth compared to the precedent year, due to the Covid-19 pandemic and the consequent travelling restrictions applied globally.

Data regarding the population in the geographical area served by the airport is taken from the World Urbanization Prospect of 2018 provided by the Population Division of the Department of Economic and Social Affairs of the United Nations. The average per capita income of the geographical region around the airport is obtained from the World Development Indicators datasets published by the World Bank. The list of continuous variables and their description is contained in Table 1.

Variables' name	***Description***	***Type of variable***
`dep_seats`	Total number of seats per route divided by the number of departure flights.	Endogenous variable
`totalCO2_tonnes`	Total CO2 emitted during the round-trip flight.	Endogenous variable
`pax_charge`	Total sum of the airport charges per round-trip divided by the number of seats of the aircraft.	Exogenous variable

`income_dep_airport`	Per-capita average income in the region of the departure airport (in a yearly basis).	Exogenous variable
`pop_dep_airport`	Population in the region around the airport of departure (in a yearly basis).	Exogenous variable
`income_dest_airport`	Per-capita average income in the region of the destination airport (in a yearly basis).	Exogenous variable
`pop_dest_airport`	Population in the region around the airport of destination (in a yearly basis).	Exogenous variable

Table 1: List of Variables.

The data is merged and subsequently partitioned into two separate datasets based on flight distance. The objective is to compute distinct environmental charges, contingent on the flight's duration, recognizing that long-haul flights contribute more to pollution due to their extended time in the air and the use of larger aircraft with higher passenger capacities.

The graphical representation of the average charge per passenger for medium- and long-haul in Figure 3 and 4 respectively shows that charges in European countries and North America (United States and Canada) are the highest, especially for long distance flights.

The difference in the cost for airline companies is remarkable, for example a round-trip flight from Orlando International Airport (United States) to Frankfurt International Airport has an average charge for passenger of 84.32 €, while from Chhatrapati Shivaji Maharaj International Airport (Mumbai, India) for the same destination is only 22.39 € per passenger (nearly four times lower). The differences among the statistical values

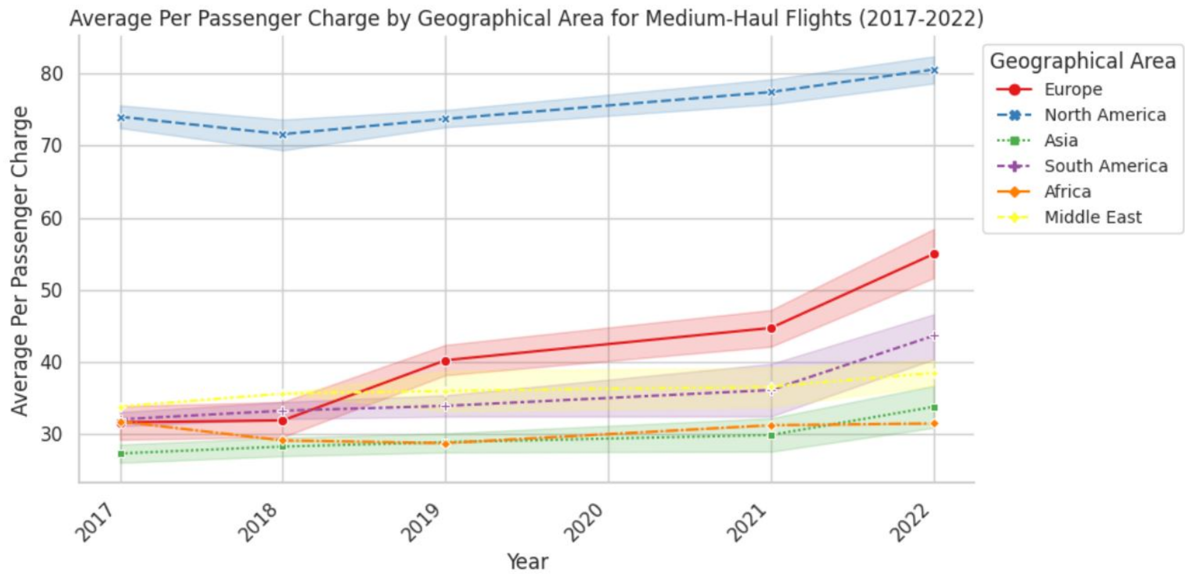

Figure 3: Line chart of the average charge per passenger for medium-haul flights divided by continent through the years between 2017 and 2022.

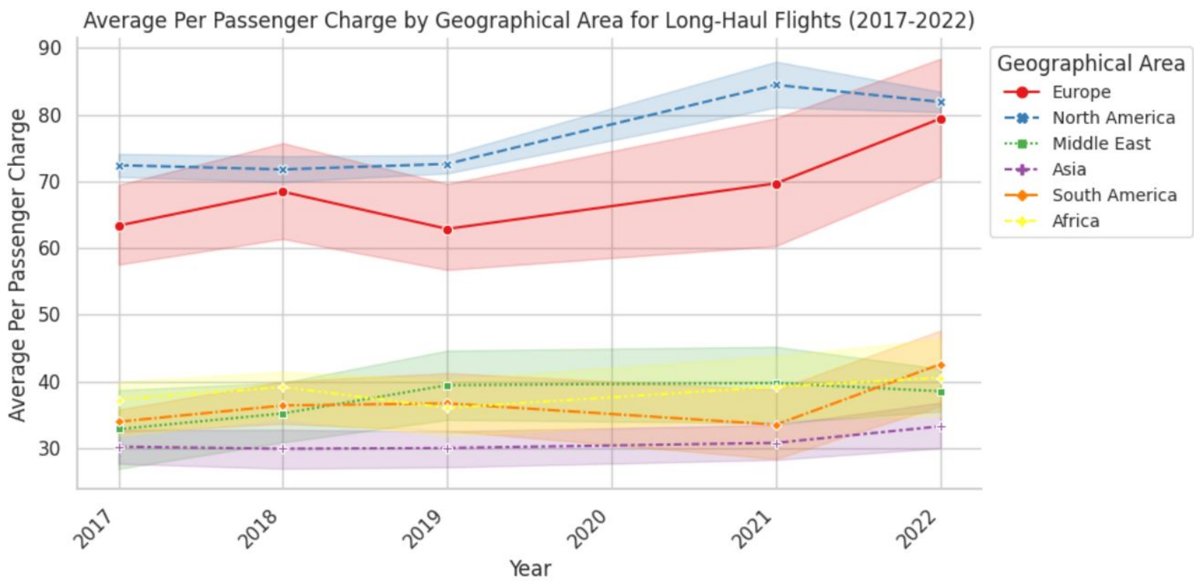

Figure 4: Line chart of the average charge per passenger for long-haul flights divided by continent through the years between 2017 and 2022.

for the variables used in the model between the four different scenarios are compared in Table 6 and 7 in Appendix 1.
For this reason I decide to divide between two markets: the former composed by Europe, US and Canada airports as a starting point, the latter formed by airports located in all remaining countries. Finally, I obtain four different scenarios with data regarding:

1. Medium-haul flights departing from European and North America airports.
2. Medium-haul flights departing from all other countries airports.
3. Long-haul flights departing from European and North America airports.
4. Long-haul flights departing from all other countries airports.

By differentiating between markets and flight duration it is possible to evaluate more precisely the supply elasticity for each combination of market and route and therefore derive a more impactful set of charges.

5 Supply Elasticity Estimation

To determine a charge that can genuinely contribute to the attainment of the 2050 net-zero emissions goal, it is necessary to start by estimating how an increase in the average charge per passenger impacts the supply elasticity of airline companies across each of the four distinct market-flight combinations.
I start from the following equation for the route-airline pair i in year t:

$$log(DepartingSeats)_{i,t} = \alpha + \beta(PaxCharge)_{i,t} + \lambda X_{i,t} + \gamma_i + \delta_t + \varepsilon_{i,t} \quad (1)$$

The dependent variable is the average number of departing seats per round-trip. α is the constant, the main explanatory variable of interest is the average charge per passenger. X comprises all control variables, that include:

- Per capita income in the area surrounding the origin airport;
- Per capita income in the area surrounding the destination airport;

- Population around the origin airport;
- Population around the destination airport.

The average fares price is not added as explanatory variable as it is commonly assumed, in aviation studies, that airlines firstly make supply decisions and then adjust fares according to the evolution of demand. Hence, fares are not considered to be an explanatory variable in supply equations.
Instead, γ and δ represent fixed effects for country and year respectively, in order to control over omitted variables that may be correlated with the data under examination. The decision of using fixed effects at the country level and not at the airport level is due to the fact that airport charging systems are in many instances imposed or otherwise regulated by national authorities. Even when the airports are privately owned, the charges have to comply with some rules established by the government authorities.
Finally, ε indicates the error term.
All continuous variables have been log-transformed to ensure robustness mitigating the influence of outliers, and facilitate the interpretation of parameter estimates as elasticities, .

5.1 Multicollinearity and Endogeneity

Visually inspecting the boxplots for each scenario it's possible to observe the presence of possible outlying data points. Once identified the outlying values through the interquantile range, just very few extreme values were dropped from the data, which were clearly errors, as it was not possible to rule out with certainty if most of them represented mistakes or truthful observations. In order to deal with these extreme values, along with the logarithmical transformation the Robust Linear Model (RLM) is used, which also accounts for heteroskedasticity.

Notably, the average charge per passenger and the average per capita income around the origin airport could exhibit correlation. As depicted in Figures 3 and 4, the regions with the highest charges (Europe and North America), also coincide with the area with the highest average per capita income levels.

In fact, among the variables considered, only the charge variable and the income in the area of the departing airport variable for both the medium- and long-haul datasets showed a Variance Inflation Factor (VIF) exceeding 5. Consequently, the income variable pertaining to the departure airport area has been removed from the analysis, resulting in all VIF values falling below the 5 threshold.

The main challenge in this economic analysis is addressing potential endogeneity bias, stemming from the correlation between the main predictor variable (average charge per passenger) and the error term of the model. This can manifest in two scenarios:

1. when critical variables are excluded from the model, resulting in omitted variable bias;
2. when the outcome variable serves as a predictor of the independent variable rather than being solely a response to it, giving rise to simultaneity bias.

A rising passenger flow and, in turn, an increased number of departures may lead the airport authority to raise charges, potentially resulting in simultaneity bias. To mitigate the bias introduced by endogeneity, an instrumental variable is incorporated into the model: airport ownership.

5.2 Instrumental Variable

The decision of using airport ownership as instrumental variable is supported by the 2017 Economic Report from IATA [19] that highlights a significant escalation in average airport charges per passenger in Europe, which surged from 16 € to 33 € during the period spanning from 2006 to 2016. During the same period the proportion of fully privately owned airports in Europe witnessed a notable increase, rising from 9% to 16%. While publicly owned airports are frequently prioritizing economic and social objectives to benefit their local communities, privately owned airports, are primarily oriented towards delivering returns to investors.
In fact, as discovered by Howell et al. 2023 [16] both private equity (PE) and non-PE ownership models are linked to increased fees compared to government ownership. Nevertheless, even with these elevated fees, there is an observed increasing trend in

traffic. One explanation found by the authors is that after privatization, runway fees increase, while passenger fees decrease. This shift encourages airlines to operate larger, more fully occupied planes.

The new variable `airport_ownership` takes four different values:

- Public: The state takes on the responsibility of investing, managing, and governing the airport.
- Private: A private company acquires the airport and operates it in accordance with market principles.
- Public-Private Partnership (PPP): A collaborative arrangement between the public and private sectors to oversee airport services. The participation in the airports capital of the private sector is typically less than 50%.
- US model: US airports are a special form of PPP in which the runways are managed by public entities, while the terminals are usually owned by the airlines.

There is a correlation between airport ownership and the average charge per passenger. Airports under private ownership or operating as part of a private-public partnership tend to charge higher costs compared to public airports. However, this correlation is not directly related to the error term in the model, so it should be a good instrument.
The distribution among the various ownership types is relatively balanced: 38 airports fall under public ownership, 11 are private, 14 operate as public-private partnerships, and 24 follow the U.S. model.
The new supply elasticity estimation, now, is given by the following equation for the route-airline pair i in year t:

$$log(DepartingSeats)_{i,t} = \alpha + \beta(PaxCharge)_{i,t} + \lambda X_{i,t} + \phi IV + \gamma_i + \delta_t + \varepsilon_{i,t} \quad (2)$$

where IV is a dummy variable for each type of airport ownership.
The coefficient β measures the supply elasticity of airlines, which is expected to be negative. The method with which the equation is estimated is Two-Stage Least-Squares

(2SLS). The regression model is analysed in the next section.

5.3 Two Stage Least Squares Model

Two-Stage Least-Squares (2SLS) is a statistical method that leverages instrumental variables (IVs) to address endogeneity in regression analysis. It is divided in two stages that consist of running two separate regressions. I use a Robust Linear Model (RLM) with Huber estimator as robust criterion function for down-weighting outliers (Huber, P., 1964 [13]) for both stages. The first stage of 2SLS consists of using the IVs and the other control variables as regressors for the charge per passenger variable (`pax_charge`). In the second stage, the coefficients computed in the first stage are employed together with the other control variables and the IVs to estimate the departing seats variable.

Stage 1:

$$Pax\hat{C}harge_{i,t} = \alpha + \lambda X_{i,t} + \phi IV + \gamma_i + \delta_t + \varepsilon_{i,t} \tag{3}$$

Stage 2:

$$Depart\hat{i}ngSeats_{i,t} = \alpha + \beta Pax\hat{C}harge_{i,t} + \lambda X_{i,t} + \phi IV + \gamma_i + \delta_t + \varepsilon_{i,t} \tag{4}$$

where $Pax\hat{C}harge$ is the vector of fitted values from the first-stage regression. In the first stage I verify the relevance condition. All four dummy variables for airport ownership have p-value = 0.000, so they are a good instrument and I can proceed to the second stage.
The results of the second stage of 2SLS for medium and long-haul flights for Europe and North America are summarized in Table 2, and in Table 3 for the other countries.
If the coefficient linked to the passenger charge variable in the supply equation is less than one, it signifies that the supply elasticity is inelastic. Conversely, if the coefficient is greater than one, it indicates an elastic supply.

For Europe and North America, the results in Table 2's first column reveals that a 1% rise in the average charge per passenger leads to a statistically significant -0.83% de-

Table 2: Supply elasticity of airline companies in Europe and North America

	Medium-haul flights	***Long-haul flights***
Constant	6.8345***	21.5229***
	(1.5742)	(6.8274)
Average Charge per Passenger	-0.8387***	0.4927
	(0.3061)	(0.9483)
Population in the Region around the Airport of Departure	0.3247***	0.1995***
	(0.0395)	(0.0520)
Per Capita Income in the Region of the Destination Airport	-0.1370**	-1.2888
	(0.0657)	(0.8454)
Population in the Region around the Airport of Destination	0.1978***	-0.0909**
	(0.0490)	(0.0367)
Country Fixed Effects	YES	YES
Year Fixed Effects	YES	YES

Standard errors in parentheses. * p<.1, ** p<.05, ***p<.01

cline in departing seats for medium-haul flight (with a p-value of 0.000).
However, the second column presents a positive coefficient that is not statistically significant (p-value = 0.9483). Therefore, it is not possible to make reliable inferences regarding how charge increments affect the supply of long-haul flights by airline companies. This lack of statistical significance may be attributed to the considerable heterogeneity within the dataset for long-haul flights, encompassing flights ranging from 6 to 16 hours in duration, resulting in substantial variation in charge and emission values or simply that a a non linear model should be preferred to carry out the analysis.

The outcomes in Table 3 for the remaining countries also provide no clear evidence. In the case of medium-haul flights, a 1% increase in the average charge per passenger appears to lead to a -0.33% reduction in departing seats. However, this result lacks statistical significance (with a p-value of 0.8748). Conversely, for long-haul flights, the coefficient is statistically significant at 99% confidence level, but the economic interpretation is counterintuitive. It suggests that a 1% increase in the charge per passenger should result in a 3.12% increase in departing seats. This result, once again, likely stems from the wide variation in charge and emission values observed in the data for long-haul flights or the necessity of fitting a different model. Furthermore, the remaining countries exhibit substantial heterogeneity, characterized by varying income and

Table 3: Supply elasticity of airline companies in the other countries.

	Medium-haul flights	***Long-haul flights***
Constant	-0.3126	1.4566**
	(0.4087)	(0.6530)
Average Charge per Passenger	-0.3344	3.1219***
	(0.8748)	(1.2089)
Population in the Region around the Airport of Departure	0.3189***	1.0513***
	(0.1229)	(0.2173)
Per Capita Income in the Region of the Destination Airport	-0.0975*	-1.8947***
	(0.0585)	(0.5964)
Population in the Region around the Airport of Destination	0.4545**	0.0721
	(0.2290)	(0.1320)
Country Fixed Effects	YES	YES
Year Fixed Effects	YES	YES

Standard errors in parentheses. * p<.1, ** p<.05, ***p<.01

population levels.

6 CO2 Emissions Estimation

To directly assess the influence of an additional environmental charge on CO2 emissions, I employ the same regression model, but with the total tonnes of CO2 emitted per round trip as dependent variable. Continuous variables are logarithmically transformed to mitigate the impact of outliers, enabling the interpretation of results in terms of percentages.

The model employed is once again the Two-Stage Least Squares, incorporating year and country fixed effects. Additionally, airport ownership is introduced as an instrumental variable. The model is expressed by the following equation for the airline-route pairs i and year t:

$$ltotCO2_{i,t} = \alpha + \beta(PaxCharge)_{i,t} + \lambda X_{i,t} + \phi IV + \gamma_i + \delta_t + \varepsilon_{i,t} \tag{5}$$

$totCO2$ is the total CO2 emitted per round-trip flight expressed in tonnes. The main explanatory variable of interest is the average charge per passenger. X comprises all

Table 4: CO_2 Estimation Impact of Charge Increment on CO_2 Emissions.

	Total CO2 emitted (tonnes)
Constant	6.9639***
	(1.6505)
Average Charge per Passenger	-1.3898***
	(0.3209)
Population in the Region around the Airport of Departure	0.4028***
	(0.0414)
Per Capita Income in the Region of the Destination Airport	-0.1976***
	(0.0688)
Population in the Region around the Destination Airport	0.1743***
	(0.0514)
Country fixed Effects	YES
Year Fixed Effects	YES

Standard errors in parentheses. * $p<.1$, ** $p<.05$, *** $p<.01$

control variables, that include:

- Per capita income in the area surrounding the destination airport;
- Population around the origin airport;
- Population around the destination airport.

Per capita income in the area surrounding the origin airport is excluded again to avoid multicollinearity. All variables are transformed logarithmically. The equation is applied only to medium-haul flights for flights departing from Europe and North America, the only market in which significant and conclusive result are obtained in equation 4. The instrumental variable is incorporated to avoid endogeneity.

Remarkably, a 1% increase in current charges corresponds to a statistically significant 1.39% reduction in CO_2 tonnes of emissions produced. This result is aligned with the expectations. The reduction in flight departures as indicated in Table 2, leads to an immediate reduction in CO_2 emissions.

7 Environmental Charge Estimation

In March 2022, ICAO published a report on the feasibility of a long-term aspirational goal (LTAG) for international civil aviation CO2 emission reductions [4], which has the scope to evaluate the capacity of the aviation sector of reaching carbon-neutrality in 2050. The study looked at various integrated scenarios combining in-sector measures (technology, operations and fuels) and provided predictions for 2050 and 2070. While none of the scenarios in the study reached zero CO2 emissions in 2050, the most ambitious one (IS3) led to residual CO2 emissions of around 200 million tonnes (i.e. around 90% less than the baseline “do nothing” scenario or one third of emissions in 2019). To have a criterion for comparison these estimates can be compared with carbon-offsetting pathway prediction evaluated by the International Air Transport Association (IATA) that designed a potential schedule towards net-zero for the aviation sector. The forecast shows the megatonnes (Mt)[8] of CO2 emissions that need to be offset every five years until 2050 to meet the Paris Agreement goal, as reported in Figure 5.

As it can be observed in Table 5 the quantity of emissions that needs to be offset in 2050 is remarkably higher. The necessity of implementing a different approach to reach the goal established is blunt.

The quantities reported in Table 5 are at global level, while the environmental charge, as designed in this thesis, changes based on the scenario, depending on the type of flight (medium/long-haul) and the departing country. Once the proportion of CO2 emitted yearly in each scenario is known, and once equations 4 and 5 are estimated it becomes feasible to determine the exact quantity of environmental charge needed to motivate airline companies to adjust their supply in line with the specific emission reduction objectives within each scenario.

To make a practical example I apply the results obtained in Table 2 and 4 for medium-haul flights in Europe (1% charge increase leads to a reduction in -1.39% emissions).

[8] A megatonne is equivalent to 1.000.000 tonnes

DATE	AMOUNT OF CO_2 ABATEMENT	PATHWAY	ACTION
2025	**381 megatonnes (Mt)** (2021-2025)	97% offsets, 2% SAF, 1% improvements above business as usual (BAU)	ICAO agree long-term goal for international aviation (2022); energy sector commits to at least 6 million tonnes SAF production; agreement of full implementation of Article of Paris Agreement
2030	**979 Mt** (2026-2030)	93% offsets; 5% SAF, 2% Improvements above BAU	Use of 100% SAF on aircraft, ANSPs fully implement ICAO Aviation System Block upgrades to deliver fuel efficiency improvements of 0.3% by 2030
2035	**1,703 Mt** (2031–2035)	77.5% offsets, 17.5% SAF, 3% improvements above BAU, 2% Carbon Capture Utilization and Storage (CCUS)	Evolutionary technology achieving 30% reduction in fuel burn, electric/hydrogen aircraft for regional markets (50-100 seats, 30-90 min flights) become available
2040	**3,824 Mt** (2036-2040)	44.5% offsets, 40% SAF, 7.5% non drop-in fuel (new propulsion technologies), 5% CCUS, 3% improvements above BAU	Feasibility of new aircraft such as blended-wing bodies demonstrated with full-scale working prototypes, electric/hydrogen for short-haul markets (100-150 seats, 45-120 min flights) become available.
2045	**6,153 Mt** (2041-2045)	55% SAF, 24% offsets, 10% non drop-in fuel, 8% CCUS, 3% improvements above BAU	Necessary infrastructure for new energy requirements (low carbon electricity/hydrogen) becomes available
2050	**8,164 Mt** (2046-2050)	**65% SAF**, 13% non drop-in fuel, 11% CCUS, 8% offsets, 3% improvements above BAU	Commercially viable annual SAF production of 449 billion litres available

Figure 5: IATA prediction of the carbon-offsetting pathway until 2050 based on ICAO's basket of measure.

According to the European Union Aviation Safety Agency (EASA)[9] the CO2 emissions of all flights departing from European Union Members plus the European Free Trade Association (EFTA)[10] airports reached 137 million tonnes[11] in 2019. Medium-haul flights represented approximately 19% of departures during 2019 and 23% of all CO2 and NOx emissions, so around 31.51 megatonnes. As forecast by CAEP [4] aviation will recover to 2019 levels in 2024 following the mid scenario estimates. So, 15% of 31.51 is the

[9]The European Union Aviation Safety Agency is an agency of the European Union with responsibility for civil aviation safety. It carries out certification, regulation and standardisation and also performs investigation and monitoring.

[10]The European Free Trade Association (EFTA) is a regional trade organization and free trade area consisting of four European states: Iceland, Liechtenstein, Norway and Switzerland.

[11]147 megatonnes if counting also cargo flights, but the environmental charge is applied only to civil aviation, so cargo emissions are excluded.

quantity that needs to be reduced in 2024, as the CNG2020 goal is to keep emissions at 85% of 2019 levels, which is equal to 4.7265 megatonnes. So 1% increase causes a drop in 0.438 megatonnes[12]. The charge is calculated for round trip so it needs to be halved to account for only departing flights, which means that to reduce 4.7265 megatonnes of emissions, the actual charge per passenger should increase by 5.39 times. As reported in Table 5, in the years 2021-2025 97% of emissions should be offset by CORSIA, so in conclusion the charge should increase of 5.23[13] times. This means for example that the charge per passenger on the flight from Stockholm - Arlanda Airport to Lisbon Airport should increase from 7.89 € to 41.28 €.

The charge is meant to gradually decrease in the years as Sustainable-Aviation-Fuels (SAF) substitute fossil fuels and operational improvements enhance efficiency in aviation. However, the environmental charge might be too high to be economically sustainable for airlines, especially in the first years, when companies also have to invest in SAF and general improvements.

A way to mitigate this issue would be to use the revenue generated from the environmental charge to finance technological research and investments in SAF or carbon offsetting initiatives, akin to the offsetting initiatives contemplated by CORSIA. By reinvesting this revenue back into technological and sustainable efforts or allocating it to CO2 reduction projects, this strategy allows airline companies a more gradual and adaptive transition to the new policy. Furthermore, this investment can facilitate further reduction of CO2 emissions in the atmosphere, thereby advancing progress toward the attainment of the CO2 reduction targets necessary to align with the objectives of the Paris Agreement.

8 Conclusions

The urgency of addressing climate change has pushed countries and international organizations to take countermeasures against CO2 emissions in the most polluting industries. The aviation sector's rapid expansion, coupled with its potential environmental

[12] The result is obtained by $31.51 \times 0.0139 = 0.438$

[13] 5.23 is 97% of 5.39

impact, is one of them. The constant growth in air traffic is expected to continue, making it crucial to assess and mitigate the sector's environmental footprint.
The efforts put in place so far to invert this trend have been insufficient. One such initiative is CNG2020 conceived by ICAO, during its 39^{th} Assembly in 2016, which aims at keeping emissions under 85% of CO2 released globally by civil aviation in 2019. Evidences from various studies have demonstrated this target to not be enough to meet the Paris Agreement goal of maximum 1.5 Celsius degrees increment. So, ICAO has set a more ambitious target declaring a long-term aspirational goal of carbon neutrality in 2050 and provided a set of measures to reach it. CORSIA, is a global market-based mechanism that aims to offset emissions that cannot be reduced through fuel effi ciency improvement, operational enhancements and the adoption of sustainable aviation fuels. However, there are concerns about its effectiveness in achieving net-zero emissions, as CO2 is not directly reduced, but it's rather offset every three years through the purchase of emission units from sustainable projects.

Regrettably, we find ourselves in a situation where the luxury of time is a resource we can no longer afford to waste. The urgency of addressing climate change and reducing the environmental impact of industries like aviation has reached a critical juncture. There is no longer room for trial and error or the implementation of ineffective measures.
An alternative to CORSIA is the global implementation of an environmental charge, effectively increasing existing airport fees. This approach has the advantage of directly reducing emissions at the source, instead of compensating them later.
The primary step is to examine how airlines respond to changes in airport charges in different scenarios. The results reveal that, for medium-haul flights departing from Europe or North America, a 1% increase in charges leads to a reduction in -0.83% departing seats and a subsequent -1.39% decrease in tonnes of emissions. Based on this result it can be estimated that in 2024 the introduction of an effective environmental charge would increase 5.23 times the current charge per passenger. However, in other scenarios, the results lack statistical significance, largely due to the data heterogeneity.
While the cost increase for airlines and passengers may be substantial, the revenue generated from these charges can be reinvested in research for sustainable aviation

technologies and fuels. Additionally, the charges are intended to decrease gradually as airlines adopt more sustainable practices.

Unfortunately, it is not possible to provide a similar estimation for the other scenarios, as the results for the supply elasticity estimation is not significant. A way to improve these results, could be, instead of generally refer to long-haul flights, to differentiate among flights based on ranges of Km travelled, in order to obtain more homogeneous data. Also exploring different models such as quantile regression and evaluating the different impact for low-cost and full-carriers is an interesting and useful expansion of this work for the future.

In conclusion, this thesis offers a practical approach that can complement existing measures and help the aviation industry transition towards a more sustainable and environmentally responsible future, suggesting that, with targeted increases in charges, it is possible to effectively reduce emissions in the sector. The urgency of addressing climate change makes such initiatives crucial, and this study takes a step in that direction, hoping that more will follow.

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9 Appendix 1

Table 5: List of airports analyzed.

	Airport	City	Country	Geographical Area	Airport Ownership
0	Amsterdam - Schiphol	Amsterdam	Netherlands	Europe	public
1	Stockholm - Arlanda	Stockholm	Sweden	Europe	public
2	Athens - Eleftherios Venizelos International	Athens	Greece	Europe	ppp
3	Hartsfield-Jackson Atlanta International	Atlanta	United States	North America	US
4	Abu Dhabi International	Abu Dhabi	United Arab Emirates	Middle East	public
5	Barcelona	Barcelona	Spain and Canary Islands	Europe	ppp
6	Bangkok - Suvarnabhumi International	Bangkok	Thailand	Asia	public
7	Bogota - Eldorado	Bogota	Colombia	South America	public
8	Mumbai	Mumbai	India	Asia	public
9	Boston - Logan International	Boston	United States	North America	US
10	Brussels - National	Brussels	Belgium	Europe	private
11	Cairo International	Cairo	Egypt	Africa	public
12	Guangzhou - Baiyun	Guangzhou	China	Asia	public

13	Paris - Charles De Gaulle	Paris	France	Europe	ppp
14	Charlotte - Douglas	Charlotte	United States	North America	US
15	Copenhagen	Copenhagen	Denmark	Europe	private
16	Delhi - Indira Gandhi International	Delhi	India	Asia	public
17	Denver International	Denver	United States	North America	US
18	Dallas/Ft. Worth International	Dallas	United States	North America	US
19	Hamad International	Doha	Qatar	Middle East	public
20	Detroit - Wayne County	Detroit	United States	North America	US
21	Dublin	Dublin	Ireland	Europe	public
22	Dusseldorf	Dusseldorf	Germany	Europe	ppp
23	Dubai	Dubai	United Arab Emirates	Middle East	public
24	New York - Newark Liberty International	New York	United States	North America	US
25	Rome - Fiumicino	Rome	Italy	Europe	private
26	Fort Lauderdale-Hollywood International	Fort Lauderdale	United States	North America	US
27	Frankfurt International	Frankfurt	Germany	Europe	ppp

28	Sao Paulo - Guarulhos International	Sao Paulo	Brazil	South America	private
29	Geneva - Cointrin	Geneva	Switzerland	Europe	public
30	Hamburg	Hamburg	Germany	Europe	ppp
31	Helsinki-Vantaa	Helsinki	Finland	Europe	public
32	Hong Kong International	Hong Kong	Hong Kong	Asia	ppp
33	Washington - Dulles International	Washington	United States	North America	US
34	Houston - George Bush Intercontinental	Houston	United States	North America	US
35	Seoul - Incheon International	Seoul	Republic of Korea	Asia	public
36	Jeddah - King Abdulaziz International	Jeddah	Saudi Arabia	Middle East	public
37	New York - John F. Kennedy International	New York	United States	North America	US
38	Johannesburg - O.R. Tambo International	Johannesburg	South Africa	Africa	public
39	Osaka - Kansai International	Osaka	Japan	Asia	private
40	Kuala Lumpur International	Kuala Lumpur	Malaysia	Asia	public
41	Kuwait International	Kuwait	Kuwait	Middle East	public

42	Las Vegas - Harry Reid International	Las Vegas	United States	North America	US
43	Los Angeles International	Los Angeles	United States	North America	US
44	London - Gatwick	London	United Kingdom, UK	Europe	private
45	London - Heathrow	London	United Kingdom, UK	Europe	private
46	Lima - J Chavez International	Lima	Peru	South America	private
47	Lisbon	Lisbon	Portugal	Europe	private
48	Madrid - Barajas	Madrid	Spain and Canary Islands	Europe	ppp
49	Manchester International	Manchester	United Kingdom, UK	Europe	public
50	Orlando International	Orlando	United States	North America	US
51	Muscat International	Muscat	Oman	Middle East	public
52	Mexico City - Juarez International	Mexico City	Mexico	South America	public
53	Miami International	Miami	United States	North America	US
54	Minneapolis - St Paul International	Minneapolis	United States	North America	US
55	Munich - Franz Josef Strauss	Munich	Germany	Europe	public
56	Milan - Malpensa	Milan	Italy	Europe	ppp
57	Tokyo - Narita	Tokyo	Japan	Asia	private

58	Chicago - O'Hare International	Chicago	United States	North America	US
59	Oslo	Oslo	Norway	Europe	public
60	Portland International	Portland	United States	North America	US
61	Beijing - Capital	Beijing	China	Asia	public
62	Philadelphia International	Philadelphia	United States	North America	US
63	Palma Mallorca	Palma De Mallorca	Spain and Canary Islands	Europe	ppp
64	Prague - Ruzyne	Prague	Czech Republic	Europe	public
65	Shanghai - Pu Dong	Shanghai	China	Asia	public
66	Riyadh - King Khaled International	Riyadh	Saudi Arabia	Middle East	public
67	San Diego International	San Diego	United States	North America	US
68	Santiago - Arturo Merino Benitez	Santiago	Chile	South America	public
69	Seattle/Tacoma International	Seattle	United States	North America	US
70	San Francisco International	San Francisco	United States	North America	US
71	Singapore - Changi	Singapore	Singapore	Asia	public
72	Salt Lake City International	Salt Lake City	United States	North America	US
73	London - Stansted	London	United Kingdom, UK	Europe	private

74	Vienna International	Vienna	Austria	Europe	ppp
75	Warsaw - Frederic Chopin	Warsaw	Poland	Europe	public
76	Montreal - Pierre Elliott Trudeau International	Montreal	Canada	North America	public
77	Vancouver International	Vancouver	Canada	North America	public
78	Calgary International	Calgary	Canada	North America	public
79	Toronto - Pearson International	Toronto	Canada	North America	public
80	Zurich	Zurich	Switzerland	Europe	ppp
81	Malaga	Malaga	Spain and Canary Islands	Europe	ppp
82	Istanbul - New	Istanbul	Turkey	Middle East	public
83	Tel Aviv - Ben Gurion International	Tel Aviv	Israel	Middle East	public
84	Berlin - Brandenburg	Berlin	Germany	Europe	public
85	Paris - Orly	Paris	France	Europe	ppp
86	Tampa International	Tampa	United States	North America	US

Table 6: Descriptive statistics for medium-haul flights.

Continuous variables	mean	std	min	25%	50%	75%	max
Europe and North America							
Departing Seats	29385.08	28747.41	126.00	12425.46	21177.00	38993.20	369600.00
Total CO2[14]	5241.24	8373.74	20.22	1757.45	3343.01	5936.25	145967.58
Average Charge per Passenger	54.17	24.83	14.97	34.78	53.04	72.97	124.76
Population around the Departure Airport	14.63	1.14	11.82	13.55	14.69	15.61	16.75
Per Capita Average Income around the Departure Airport	9.59	0.65	8.66	9.11	9.18	9.99	11.31
Population around the Destination Airport	15.96	1.03	13.31	14.88	16.52	16.88	16.91
Other countries							
Departing Seats	46464.57	42110.98	144.00	20533.33	34523.00	60028.67	486710.00
Total CO2	9456.68	8445.41	22.42	3801.55	6412.29	12805.26	79400.91
Average Charge per Passenger	32.26	10.49	4.73	26.16	30.40	38.47	56.45
Population around the Departure Airport	15.94	0.98	12.93	15.57	16.14	16.77	17.20
Per Capita Income around the Departure Airport	9.17	0.86	7.51	8.74	8.89	9.18	10.97
Population around the Destination Airport	16.29	0.43	14.85	16.11	16.15	16.59	17.28

Data for Income and Population variables is transformed in log form for better readability.

Table 7: Descriptive statistics for long-haul flights.

Continuous variables	mean	std	min	25%	50%	75%	max
Europe and North America							
Departing Seats	51680.11	41798.99	271.00	26107.00	39815.50	64627.00	367552.00
CO2 Emissions	26902.41	25410.59	100.84	12350.07	19851.54	33423.02	242501.27
Average Charge per Passenger	72.43	33.42	14.92	49.52	71.31	83.09	192.61
Population around the Departure Airport	15.14	0.98	11.82	14.74	15.28	15.70	16.75
Per Capita Income around the Departure Airport	10.84	0.21	10.55	10.64	10.77	11.07	11.10
Population around the Destination Airport	16.09	0.99	13.51	16.01	16.30	16.75	16.75
Other countries							
Departing Seats	59923.58	51574.35	174.00	28014.25	45136.00	74724.00	292651.50
Total CO2	36328.90	29252.17	36.53	14484.20	30394.65	50556.86	149549.62
Average Charge per Passenger	34.22	12.01	6.07	27.44	34.41	41.45	63.91
Population around the Departure Airport	15.80	1.16	12.88	15.29	16.11	16.81	17.28
Per Capita Income around the Departure Airport	10.68	0.15	10.55	10.58	10.63	10.66	11.10
Population around the Destination Airport	16.02	0.69	13.51	16.00	16.30	16.30	16.75

Data for Income and Population variables is transformed in log form for better readability.