Transportation Research Part A 162 (2022) 236–252

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Synthetic control methods for policy analysis: Evaluating the effect of the European Emission Trading System on aviation supply

Yicheng Kang [a], Sha Liao [b], Changmin Jiang [c,d], Tiziana D'Alfonso [e,*]

[a] Farmer School of Business, Miami University, United States
[b] School of Business, University of the Fraser Valley, Canada
[c] School of International Trade and Economics, University of International Business and Economics, Beijing, China
[d] Research Center for Environment and Sustainable Development of the China Civil Aviation
[e] Department of Computer Control and Management Engineering, Sapienza University of Rome, Via Ariosto 25, 00185, Rome, Italy

ARTICLE INFO

Keywords:
Carbon pricing
Aviation
Climate policy
Synthetic controls
Differences in differences
Matching

ABSTRACT

In this paper, we provide a novel application of synthetic control methods by offering two major modifications to the existing methodological framework. We provide the first complete ex-post evaluation of the causal impact of carbon pricing on aviation supply, expressed in terms of airline output (i.e., number of seats supplied at the airline-route level). We investigated the policy change in the European Union Emission Trading System (EU ETS), the first large greenhouse gas emissions trading scheme in the world. We distinguish between low-cost, regional and full service airlines, short and medium/long-haul routes, routes towards (or from) hub airports versus non-hub airports, monopolistic versus non-monopolistic routes. The analysis shows that the EU ETS does not have a substantial impact on the average aircraft size, while it has caused a reduction of total airline seat capacity and flight frequency, with the percentage of airline seat capacity reduction reaching above 20% at its peak. The overall effect of the policy has a remarkable impact on low-cost and regional airlines, short-haul routes, spoke–spoke markets and monopolistic routes. Our results are the first empirical confirmation to the theoretical prediction in the aviation literature that emission charges will reduce flight frequency and increase load factors while having no effect on aircraft size.

1. Introduction

Social scientists are often concerned about the impacts of events or policy interventions that take place at an aggregate level and affect aggregate entities, such as firms, or geographic or administrative areas (countries, regions, cities, etc.). To estimate the effects of these interventions, researchers often use comparative case studies. In comparative case studies, scholars estimate the evolution of aggregate outcomes (such as average profitability) for a unit affected by a particular occurrence of the event or intervention of interest and compare it to the evolution of the same aggregates estimated for some control group of unaffected units. A major requirement in such comparison is that the unaffected units are able to reproduce the counterfactual outcome trajectory that the affected units would have experienced in the absence of the intervention. To achieve this purpose, several approaches have been proposed in the econometric and statistical literature. Among those approaches, the propensity-based matching proposed by Rosenbaum and Rubin (1983) has been commonly adopted in comparative studies (e.g., Abadie 2005, Angrist and Pischke 2008, Rubin 2001). The idea behind propensity-based matching is that, for each unit in the treatment group, a unit in the control group is found that bears similarities with the treatment unit using observed quantifiable characteristics.

* Corresponding author.
E-mail address: tiziana.dalfonso@uniroma1.it (T. D'Alfonso).

https://doi.org/10.1016/j.tra.2022.05.015

Available online 15 June 2022
0965-8564/© 2022 Elsevier Ltd. All rights reserved.

This approach works well if there exists a single unaffected unit that approximates well the affected unit in terms of the relevant characteristics. In practice, it can be difficult for datasets to satisfy this condition. More recently developed synthetic control methods (e.g., Abadie et al. 2010, 2015, Xu 2017) aim to address this issue by constructing combinations of unaffected units (i.e., synthetic controls). The idea is that a combination of unaffected units often provides a better comparison for the affected unit than any single unaffected unit alone. Because of this benefit, synthetic control methods have been increasingly used in this area of research. For example, Card (1990) has used a combination of cities in the southern United States to approximate the evolution that the Miami labor market would have experienced in the absence of the 1980 large and sudden Cuban migratory influx in Miami. Abadie and Gardeazabal (2003) have used a combination of two Spanish regions to approximate the economic growth that the Basque Country would have experienced in the absence of the terrorist conflict. Abadie et al. (2010) have used a combination of five states to approximate the tobacco consumption growth that California would have experienced in the absence of California's Proposition 99, a large-scale tobacco control program.

In this paper, we develop a novel application of the synthetic control method proposed by Abadie et al. (2010) to evaluate the causal impact of carbon pricing on aviation supply in response to the policy change in the European Union Emission Trading System (EU ETS), the first large greenhouse gas emissions trading scheme in the world. The EU ETS was launched in 2005 as a cornerstone of the EU's policy to combat climate change and is an important tool for reducing greenhouse gas emissions in a cost-effective manner. It is the world's largest and first major carbon market. Aviation has been included in the ETS in 2012, thus making carbon dioxide (CO2) emissions a new input cost for the air travel industry. In order to evaluate the effect of the EU ETS on aviation supply, we compare the evolution of the outcome between the routes affected by the EU ETS (i.e., the treatment group) and the unaffected routes (i.e., the control group). The selected aggregate outcome is expressed in terms of airline output. That is, number of seats supplied at the airline-route level. We use a combination of air routes to approximate the change in the number of seats supplied at the airline-route level that the aviation sector would have experienced in the absence of the EU ETS. We distinguish between low-cost and full-service airlines, short and long-haul routes, routes towards (or from) hub airports vs. non-hub airports, monopolistic vs. non-monopolistic routes, and, because the number of seats is a combination of flight frequency and aircraft size, we also examine the effect on average aircraft size.

In our evaluation of the EU ETS effect, synthetic control methods are particularly relevant, as each synthetic control provides the counterfactual outcome trajectory that the corresponding affected route would have experienced in the absence of the EU ETS policy. In addition, if the approximation given by synthetic controls is poor, the discrepancy (i.e., the lack-of-fit) can be computed and visualized in the time period prior to the EU ETS intervention. That is, if the fit is poor, we would know that synthetic controls are not appropriate to use in our EU ETS study. Therefore, synthetic control methods have safeguards to prevent misleading interpretations.

The contribution of our investigation is twofold. In our study, we measure an entire market reaction to carbon pricing as we investigate causal impacts of carbon pricing in the aviation sector (whose business is not limited to just one particular administrative area). Earlier studies have identified causal impacts of carbon pricing in a specific country (e.g., Wagner et al. 2014, Fowlie et al. 2012, Klemetsen et al. 2020) and at the level of the firm, with a focus on the propensity towards low-carbon investments (Rong and Lahdelma 2007, Flora and Vargiolu 2020, Deeney et al. 2021, Dou and Choi 2021). Furthermore, to the best of our knowledge, our study is the first attempt to empirically evaluate the causal impact of carbon pricing on aviation supply exploiting a policy change in the EU ETS. Specifically, we consider time-series cross-sectional data from 2007 to 2017, with 5 years of pre- and post-intervention records, respectively, including 315,193 routes in 48 countries of which 31 are regulated by the EU ETS. To have an idea of the relevance of the aviation sector and motivations for its inclusion in the EU ETS to combat climate change, according to The Air Transport Action Group (ATAG), nearly 88 million jobs were supported worldwide in aviation and related tourism before the COVID-19 pandemic. While air transport carries around 0.5% of the volume of world trade shipments, it is over 35% by value, so goods shipped by air are very high value commodities, often times perishable or time-sensitive. Emissions actually increased by 32% between 2013 and 2018 (International Civil Aviation Organization, 2019) and the ongoing growth of the sector will bring with it a critical increase in the global share of aviation emissions. In 2019, 4.5 billion passengers were carried by the world's airlines and even in the most optimistic scenario, technological progress will not be able to offset the emissions from forecasted growth in the sector (European Union Aviation Safety Agency, 2019).

Our study has also provided a novel application of the synthetic control method by making two major adjustments to the methodological framework proposed by Abadie et al. (2010). First, we offer an alternative way to provide theoretical justification for constructing the synthetic control. Because synthetic controls are weighted averages of the available control units, the method makes explicit: (i) the relative contribution of each control unit to the counterfactual of interest; and (ii) the similarities (or lack thereof) between the unit affected by the event or intervention of interest and the synthetic control, in terms of pre-intervention outcomes and other predictors of post-intervention outcomes. In the construction of the weight vector, Abadie et al. (2010) proved asymptotic consistency under the assumption that the number of pre-treatment periods approaches infinity. The asymptotic result is not relevant to our application, as our data only cover 5 pre-treatment periods (i.e., 5 years pre-ETS). We then provide a novel theoretical justification for constructing the weights based on the unbiasedness argument. Our result is relevant to applications of the synthetic control method characterized by a relatively small number of pre-treatment periods. Second, if we applied the existing methodology in Abadie et al. (2010) to our framework, the nested minimization would need to be done 53,566 times and each minimization involves the search of a weight vector of length 18,542. This approach is theoretically sound but computationally infeasible. Even with parallel computing on a computer cluster with 100 CPUs, the run time for this computational undertaking is estimated to be almost five years, making the implementation practically impossible. By implementing a stochastic approximation scheme in the given framework, we have been able to complete all the numerical optimizations in weeks.

Our analysis shows that the EU ETS does not have a substantial impact on the average aircraft size, while it has caused a reduction of total airline seat capacity and frequency, with the percentage of airline seat capacity reduction reaching above 20% at its peak. This result is reasonable in the sense that it is easier for airlines to change frequency over aircraft size. It is also consistent with existing studies, which point out that when facing a growth in demand, airlines tend to respond more by increasing frequency than by increasing aircraft size (Wei and Hansen 2007, Givoni and Rietveld 2009). Givoni and Rietveld (2010) also conclude that there is no significant effect of slot control (an indicator of airport congestion) on aircraft size. The overall effect of the policy has a remarkable impact on low-cost and regional airlines, short-haul routes, spoke–spoke markets and monopolistic routes.

The remainder of the paper is as follows. Section 2 offers an overview of the EU ETS and the allocation to the aviation sector. Section 3 provides a detailed literature review. In Section 4, we describe the methodological framework for the application of the synthetic control method to our case study. We provide theoretical justification for constructing the weights based on the unbiasedness argument in Section 4.1, while Section 4.2 proposes a stochastic approximation scheme for implementation. In Section 5 we describe our dataset while Section 6 provides an overview of results. Section 7 presents our conclusions and provides avenues for future research.

2. The EU ETS

The EU aims to be climate-neutral by 2050—an economy with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and is in line with the EU's commitment to global climate action under the Paris Agreement.[1]

To achieve climate neutrality in the EU by 2050, including the intermediate target of an at least 55% net reduction in greenhouse gas emissions by 2030, the EU ETS was launched in 2005 as the world's first international emissions trading system.[2] The EU ETS operates in all EU countries plus Iceland, Liechtenstein and Norway (European Economic Area (EEA)-European Fair Trade Association (EFTA) states). It limits emissions from approximately 10,000 installations in the power sector and manufacturing industry, as well as airlines operating between these countries, and covers around 40% of the EU's greenhouse gas emissions.

The EU ETS covers the following sectors and gases, focusing on emissions that can be measured, reported and verified with a high level of accuracy: (i) CO2 from electricity and heat generation, energy-intensive industry sectors (e.g., oil refineries, steel works), commercial aviation within the European Economic Area; (ii) nitrous oxide (N2O) from production of nitric, adipic and glyoxylic acids and glyoxal; perfluorocarbons (PFCs) from production of aluminum. While participation in the EU ETS is mandatory for companies in these sectors, in some sectors, only installations above a certain size are included and certain small installations can be excluded if governments put in place fiscal or other measures that will cut their emissions by an equivalent amount. In the aviation sector, the EU ETS will apply only to flights between airports located in the European Economic Area until 31 December 2023.

The EU ETS works on the "cap and trade" principle. A cap is set on the total amount of certain greenhouse gases that can be emitted by the installations covered by the system. The cap is reduced over time so that total emissions fall. Within the cap, installations buy or receive emissions allowances (i.e., permits), which they can trade with one another as needed. The limit on the total number of allowances available ensures that they have a value. After each year, an installation must surrender enough allowances to fully cover its emissions, otherwise heavy fines are imposed. If an installation reduces its emissions, it can keep the spare allowances to cover its future needs or sell them to another installation that is short of allowances.

Auctioning is the default method for allocating emission allowances to companies participating in the EU ETS. However, in sectors other than power generation, the transition to auctioning is taking place progressively. Some allowances continue to be allocated for free until 2020 and beyond. Over the current trading period (2013–2020), 57% of the total amount of allowances have been auctioned, while the remaining allowances are available for free allocation,[3].

2.1. Allocation to aviation

Aviation has been included in the EU ETS since 2012. The annual cap on aviation allowances for phase 3 of the EU ETS (2013–20) was originally over 210 million allowances (plus 116,524 allowances from 2014 to account for Croatia's integration). The allowances were to be distributed as follows: 82% granted for free to aircraft operators; 15% are auctioned and 3% in a special reserve for distribution to fast-growing aircraft operators and new entrants. The actual allocation of allowances was scaled down from 2013 to 2023, to take account of the temporary reduction of the scope of the EU ETS to flights between airports in the EAA. There have been three amendments to the EU ETS over this 11-year period, that have been intended to sustain momentum in the International Civil Aviation Organization (ICAO) negotiations on a global market-based measure for emissions reduction in the sector. A resolution

[1] The Paris Agreement sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2 °C and pursuing efforts to limit it to 1.5 °C. It also aims to strengthen countries' ability to deal with the impacts of climate change and support them in their efforts. The Paris Agreement is the first-ever universal, legally binding global climate change agreement, adopted at the Paris climate conference (COP21) in December 2015.

[2] The number of emissions trading systems around the world is increasing. Besides the EU emissions trading system (EU ETS), national or sub-national systems are already operating or under development in Canada, China, Japan, New Zealand, South Korea, Switzerland and the United States. For more information see: https://ec.europa.eu/clima/policies/ets/markets_en (Last retrieved: May 26, 2021).

[3] For more information on the EU ETS, see the EU ETS Handbook (Available at: https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf. Last retrieved: May 26, 2021). Please note that the information contained in the handbook reflects the status quo at the time of its publication in 2015. For more recent information on the EU ETS, see the Carbon Market Reports published annually by the Commission (for the 2020 edition please refer to: https://ec.europa.eu/clima/sites/default/files/news/docs/com_2020_740_en.pdf last retrieved: May 26, 2021).

was adopted by the 2016 ICAO Assembly for a global market-based measure—the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), that applies since 2020. From 2021 onwards, the same linear reduction factor that applies to stationary installations – 2.2% annually – will start applying to these allocations to aircraft operators. Due to the timeframe of our study (2007–2017), CORSIA would not have any implication on our analytical results. However, it is worth noting that there have been many discussions regarding the interactions between the two programs. For example, Scheelhaase et al. (2018) compare the two programs and conclude that the best option forward would be to continue the EU "Reduced Scope" regime and cover international flights by CORSIA beyond 2020. Maertens et al. (2019) run different scenarios, including continuing and discontinuing the EU ETS alongside CORSIA, and suggest that it is always better for the environment to maintain the ETS, irrespective of its form. Mai (2021) studies the challenges from the COVID-19 pandemic on both programs, recommending a hybrid option that keeps international intra-EU/European Free Trade Association (EFTA) flights under the EU ETS and integrate some of the CORSIA design features in implementation. Overall, the future of the EU ETS is undetermined at the moment.

Free allowances are allocated to approximately 500 aircraft operators who applied for free allocation by reporting independently verified tonne-kilometer data for 2010. Note that whether permits are being purchased or freely allocated is irrelevant in terms of their impact on marginal costs, as the opportunity cost remains the same. Free permits have an opportunity cost equal to the revenue that would be earned if sold on the market, and the corresponding emissions abated (Verde et al., 2019).

Allocations are based on airline efficiency in transporting passengers and cargo, calculated on the basis of a benchmark value established in the European Commission and EEA Joint Committee decisions. From 2012 to 2020, an airline receives 0.6422 allowances per 1,000 tonne-kilometers flown. The benchmark was calculated by dividing the total annual amount of free allowances by the sum of airlines' verified tonne-kilometre data that aircraft operators sent.

The original cap on aviation allowances was 95% of 2004–2006 emissions levels, as specified in the EU Directive including aviation in the EU ETS (221 million tonnes). Following the reduction in scope, the total amount of allowances issued has been around 38 million allowances, while verified CO2 emissions from aviation activities carried out between airports in the EEA have increased from 53.5 million tonnes in 2013 to 64.2 million tonnes in 2017. This means that, while intra-EEA aviation emissions have been continuing to increase, the inclusion of intra-European flights in the EU ETS has delivered around 100 million tonnes of CO2 reductions/offsets between 2012 and 2018.

3. Literature review

The body of literature relevant to our study can be broadly divided into three major streams: (i) studies analyzing the economic impact of the EU ETS on airlines strategies and performance, (ii) studies examining the airline's choice of aircraft size and frequency, and (iii) studies analyzing the impact of the fuel price paid by airlines on market outcomes. Indeed, the EU ETS generates a permit price that becomes part of an airline's cost structure. With the carrier's required outlay on emissions permits varying in step with its total fuel consumption, the permit price is effectively added to the price of fuel, even though most of the permits will be freely distributed. Thus, the planned trading system can be viewed as equivalent to a carbon-tax scheme applied to aviation, which would explicitly raise the price of fuel. As a result, regardless of whether policy interventions to limit aviation emissions follow the EU's cap-and-trade approach or rely on taxation, they can all be depicted as policies that raise the fuel price paid by airlines (Brueckner and Zhang, 2010).

A first stream of literature studies the effect of policies, with a main focus on price and non-price interventions (see Stiglitz 2019 and Hepburn et al. 2020 for relevant discussion). Earlier studies mainly contributed on the ex-ante evaluation of the impacts of carbon pricing, the CORSIA programs and EU ETS over (or in terms of): (i) unilateral regulation (e.g., Yuen and Zhang 2011); (ii) fuel consumption and carbon emissions (e.g., Fukui and Miyoshi 2017); (iii) fuel hedging (e.g., Hu et al. 2018); (iv) airlines' network reconfiguration and efficiency (e.g., Albers et al. 2009, Derigs and Illing 2013, Malina et al. 2012, Li et al. 2016); (v) the additional costs and effects on fares (e.g., Morrell 2007, Scheelhaase and Grimme 2007, Scheelhaase et al. 2010, Vespermann and Wald 2011); (vi) the macroeconomic activities (e.g., Anger 2010); (vii) abatement efforts, voluntary carbon offset and airline alliance (Nava et al. 2018, Zheng et al. 2019). Conversely, ex-post studies of the causal effect of carbon pricing on aviation supply are available in Fageda and Teixidó (2022) and Heiaas (2021). Other studies have identified causal impacts of carbon pricing in a specific country (e.g., Fowlie et al. 2012, Klemetsen et al. 2020) and at the firm level with a focus on the propensity towards low-carbon investments (Rong and Lahdelma 2007, Flora and Vargiolu 2020, Deeney et al. 2021, Dou and Choi 2021). Finally, a few studies investigate the effects of COVID-19 crisis in affecting the merits of cases for climate policies, i.e., the extent to which relative costs and benefits of introducing climate policies may have changed in the context of COVID-19, during both the crisis and the recovery period to follow (e.g., Amankwah-Amoah 2020, Mai 2021, Liao et al. 2022).

We are close to Fageda and Teixidó (2022) and Heiaas (2021) in that we also provide an ex-post study of the causal effect of carbon pricing. Heiaas (2021) explores whether the EU ETS succeeded in reducing the aviation sector emissions over the period 2012–2018 by employing a general synthetic control model to estimate a counterfactual scenario. When using jet fuel consumption as a proxy for emissions, the results indicate that on average the EU ETS led to a 10 percent increase in jet fuel consumption relative to a scenario where it was not implemented. However, the paper fails to conclude a causal relationship between EU ETS and jet fuel consumption due to drawbacks with the data. Fageda and Teixidó (2022) implement a difference-in-differences strategy on a sample based on all flights within Europe from 2010 to 2016 to examine the causal impact of the EU ETS on emissions and supply. They find that the EU ETS reduced emissions by 4.7% in the regulated routes relative to the counterfactual. The reduction in emissions is also high for low-cost airlines (−11%) but it is not statistically significant for network airlines, and short-haul flights (−10.7%). Our attempt differs from such studies in that we focus on investigating whether the EU ETS impacts on the strategic choice of operational variables such as aircraft size and frequency.

Regarding airline's choice of aircraft size and frequency, other than the previous studies that show it is easier to change frequency over aircraft size, Givoni and Rietveld (2009) prove that the presence of low cost carriers leads to using larger aircraft,[4] and that market concentration on certain routes leads to the choice of relatively large aircraft: lack of competition allows carriers to reduce frequencies. Hence in a strongly concentrated market aircraft size tends to be larger than optimum. Wei and Hansen (2007) take it a step further as they consider airlines competition in aircraft size and service frequency in duopoly markets. The authors find that the size of aircraft used by airlines in the short-haul market is smaller than that used in the long-haul market, which is mainly due to the dependence of economy of aircraft size on flight distance. In the long-haul market, demand is less than in the short-haul market, but profit is much higher, which is due to the economy of stage length in airlines' cost[5]. As for the relationship between airline network strategy and frequency/aircraft size, theoretical models show that hub-and-spoke (HS) strategies could activate a vicious cycle, with airlines reacting to more frequent delay events by (i) increasing services frequencies (to reduce passengers' schedule delay), thus worsening the congestion (Fageda and Flores-Fillol 2015, 2016); or (ii) shortening layovers for convenient flight connections, generating airport congestion due to concentration of flights (Brueckner and Lin, 2016)[6]. Wang and Wang (2019), compared a HS network, a point-to-point network (PP) and a mixed network (MX), and found that frequency may be higher under HS than PP. Moreover, because of the inclusion of congestion delays, the optimal aircraft size is smaller under HS than PP.

Finally, a related stream of literature refers to the impact of the fuel price paid by airlines on market outcomes. Some papers examine the effect of an increase in aviation fuel tax on reductions in fuel consumption and carbon emissions (Fukui and Miyoshi 2017, Hofer et al. 2010, Tol 2007). In particular, Fukui and Miyoshi (2017), using values from 2012, suggest that an increase in aviation fuel tax of 4.3 cents – which was the highest increase in aviation fuel tax in the US during the analysis period – would reduce CO2 emissions in the US by approximately 0.14–0.18% in the short run (1 year after the tax increase). However, due to the rebound effect, the percentage reduction in CO2 emissions would decrease to about 0.008–0.01% in the long run (3 years after the tax increase). Other authors have analyzed airline pricing decisions in response to fuel price changes (Brueckner and Zhang 2010, Scotti and Volta 2018, Wadud 2015). Brueckner and Zhang (2010) explored the effect of airline emissions charges on airfares, airline service quality, aircraft design features, and network structure, using a detailed and realistic theoretical model of competing duopoly airlines. These impacts are derived by analyzing the effects of an increase in the effective price of fuel, which is the path by which emissions charges will alter airline choices. The results show that emission charges will raise fares, reduce flight frequency, increase load factors, and improve aircraft fuel efficiency, while having no effect on aircraft size. Our study is similar to Brueckner and Zhang (2010) in that we explore the effect of airline emissions charges on aviation supply, in terms of airline output (i.e., frequency, aircraft size). However, analysis in Brueckner and Zhang (2010) is theoretical, while we carry out empirical testing. As such, our study is the first attempt to empirically evaluate the causal impact of carbon pricing on aviation supply following a policy change in the EU ETS.

4. Methodological framework

4.1. Synthetic control methods

Let $\mathcal{I}$ and $\mathcal{N}$ denote the set of the affected and unaffected routes, respectively. Let Y_{it}^{N} be the outcome (either seats or aircraft size) that would be observed for route i at time t in the absence of the ETS intervention, for $i \in \mathcal{I} \cup \mathcal{N}$, and time periods $t = 1, \ldots, T$. Let T_0 be the number of pre-ETS periods with $1 \leq T_0 < T$. Let Y_{it}^{I} be the outcome that would be observed for route i at time t if route i is affected by the ETS policy. For $i \in \mathcal{I} \cup \mathcal{N}$ and $t = 1, \ldots, T_0$, we have $Y_{it}^{I} = Y_{it}^{N}$. Let $\alpha_{it} = Y_{it}^{I} - Y_{it}^{N}$ be the ETS effect on route

[4] Low-cost airlines operate point-to-point route structures and most (if not all) of the routes they operate are within Europe. Full service carriers (i.e., flag carriers) are mainly network airlines which operate hub-and-spoke route structures and so concentrate traffic in a few hub airports. A given proportion of passengers on their short-haul flights (i.e.; European flights) could be connecting passengers whose final destination is a long-haul (non-European) destination. Regional airlines are carriers that operate regional aircraft to provide passenger air service to communities without sufficient demand to attract mainline service. A number of regional airlines were also previously known as commuter airlines. There are two main ways for a regional airline to do business: as an affiliated airline, contracting with a major airline, operating under their brand name (for example, Endeavor Air operates flights under the Delta Connection brand name for Delta Air Lines); operating as an independent airline under their own brand, mostly providing service to small and isolated towns, for whom the airline is the only reasonable link to a larger town. See also footnote 6 for further reference to hub-and-spoke systems.

[5] Wei and Hansen (2007) study the relationship between aircraft cost and size for large commercial passenger jets in the US. Based on a translog model, they develop an econometric cost function for aircraft operating cost and find that economies of aircraft size and stage length exist at the sample mean of their data set, and that for any given stage length there is an optimal size, which increases with stage length. The scale properties of the cost function are changed considerably if pilot unit cost is treated as endogenous, since it is correlated with size. The cost-minimizing aircraft size is therefore considerably smaller, particularly at short stage lengths, when pilot cost is treated as endogenous, and this helps to explain why airlines expect to accommodate future traffic growth with more flights instead of larger planes.

[6] HS route structures as an equilibrium of unregulated competition have often been explained with two arguments: economies of density and frequency effects. The first refers to that average cost in a direct route may decrease with the number of passengers, and the second, the frequency effect, to the fact that there are benefits for passengers of increased frequencies, e.g. reductions in schedule delay costs. In the last years, some hub airlines have shifted to "de-banked" operations: flights are scheduled to arrive at the hub and then depart as soon as they can be turned around, without waiting for a fixed time to accommodate connections. Hub de-banking increases aircraft and crew utilization, thereby reducing unit costs for the airline, although revenue losses may result from degraded passenger service, with some passengers experiencing increased connection times, increased travel times and possibly reduced frequency of service (Belobaba 2009). Note that congestion leading to flight delays is largely under the control of the airlines, since they are free to set scheduled flight durations (Brueckner et al. 2021). While airport congestion may make flights longer, this schedule adjustment prevents them from arriving late with respect to the schedule.

i at time t, and let D_{it} be an indicator that is one if route i is affected by the ETS policy at time t and zero otherwise. The observed outcome for route i at time t is

$$Y_{it} = Y_{it}^N + \alpha_{it} D_{it}.$$

The goal here is to estimate $\{\alpha_{it}, i \in \mathcal{I} \text{ and } T_0 + 1 \le t \le T\}$. For $t > T_0$,

$$\alpha_{it} = Y_{it}^I - Y_{it}^N, \quad i \in \mathcal{I}.$$

Since $\{Y_{it}^I, i \in \mathcal{I}\}$ are observed, we just need to estimate $\{Y_{it}^N, i \in \mathcal{I}\}$. Suppose that Y_{it}^N is given by the following model

$$Y_{it}^N = \delta_t + \theta_t' Z_i + \lambda_t' \mu_i + \varepsilon_{it}, \quad i \in \mathcal{I} \cup \mathcal{N}, t = 1, \dots, T, \tag{1}$$

where δ_t is an unknown function of t representing non-route-specific trend over time (e.g., seasonality), $\boldsymbol{Z}_i$ is a r-dimensional vector of observed characteristics of route i that are not affected by ETS (e.g., distance of the route, population and per capita GDP of the departure and arrival cities), $\boldsymbol{\theta}_t$ is a r-dimensional vector of unknown parameters, λ_t is an F-dimensional unobserved common factor, $\boldsymbol{\mu}_i$ is a vector of factor loadings associated with λ_t, and ε_{it} is an idiosyncratic error with mean zero. The product $\lambda_t' \boldsymbol{\mu}_i$ is often referred to as the common component of Y_{it}^N. Thus, Eq. (1) is the factor representation of the data. The factors, their loadings, as well as the idiosyncratic errors are all unobservable. In view of $\lambda_t' \boldsymbol{A}\boldsymbol{A}^{-1}\boldsymbol{\mu}_i$ for any invertible $\boldsymbol{A}$, the model identification is not possible without restrictions. A commonly used restriction in the econometrics literature (e.g., Connor and Korajczyk 1986, Stock and Watson 2002, Bai and Ng 2002, Bai 2009) is to require that $T^{-1}\sum_{t=1}^T \lambda_t \lambda_t'$ is positive definite. This restriction is also adopted in Proposition 1.

It is worth noting that model (1) generalizes the usual difference-in-differences (DiD) model that is commonly used in comparative studies. More specifically, if we further restrict λ_t in (1) to be constant with respect to t and define the difference variable $\Delta Y_i = Y_{it} - Y_{i1}$ for any $t > T_0$, then we have

$$\Delta Y_i = \delta^* + \theta^{*\prime} Z_i + \alpha_i^* D_i^* + \varepsilon_i^*, \quad i \in \mathcal{I} \cup \mathcal{N}, \tag{2}$$

where $\delta^* = \delta_t - \delta_1$, $\theta^* = \theta_t - \theta_1$, $\alpha_i^* = \alpha_{it}$, $D_i^* = D_{it}$, and $\varepsilon_i^* = \varepsilon_{it} - \varepsilon_{i1}$. Fitting the regression model (2) to observations $\{(\boldsymbol{Z}_i', D_i^*, \Delta Y_i), i \in \mathcal{I} \cup \mathcal{N}\}$ yields the DiD estimate for α_{it}. Therefore, the traditional DiD model can be obtained by imposing that λ_t in model (1) is constant. That is, the DiD model allows for the presence of unobserved confounders but restricts that the effect of those confounders to be unchanged over time, so they can be eliminated by taking time differences. In contrast, model (1) allows the effects of the unobserved characteristics to vary with time, so it is more flexible to use in practice.

Next, we describe the synthetic control method in detail. For each $i \in \mathcal{I}$, consider a J-dimensional vector of weights $\boldsymbol{w}^{(i)} = (w_1^{(i)}, \dots, w_J^{(i)})'$, where J is the number of routes in $\mathcal{N}$ and $\sum_{j=1}^J w_j^{(i)} = 1$ and $w_j^{(i)} \ge 0$ for $j = 1, \dots, J$. A particular value of $\boldsymbol{w}^{(i)}$ represents a potential synthetic control for route i. Thus, a synthetic control is a particular weighted average of unaffected routes. The value of the outcome for the synthetic control indexed by $\boldsymbol{w}^{(i)}$ is

$$\sum_{j\in\mathcal{N}} w_j^{(i)} Y_{jt} = \delta_t + \theta_t' \sum_{j\in\mathcal{N}} w_j^{(i)} \boldsymbol{Z}_j + \lambda_t' \sum_{j\in\mathcal{N}} w_j^{(i)} \boldsymbol{\mu}_j + \sum_{j\in\mathcal{N}} w_j^{(i)} \varepsilon_{jt}.$$

The following proposition provides some insight into the construction of the weight vector $\boldsymbol{w}$.

Proposition 1. *Suppose that there exists a* $\widetilde{\boldsymbol{w}}^{(i)} = (\widetilde{w}_1^{(i)}, \dots, \widetilde{w}_J^{(i)})'$ *such that*

$$\sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} Y_{jt} = Y_{it}, \quad t = 1, \dots, T_0, \text{ and } \sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} Z_j = Z_i. \tag{3}$$

If $\sum_{t=1}^{T_0} \lambda_t \lambda_t'$ *is invertible, then* $\mathrm{E}\left\{\sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} Y_{jt}\right\} = \mathrm{E}\left\{Y_{it}^N\right\}$.

The proof is given in the appendix. It follows from Proposition 1 that, for any $i \in \mathcal{I}$,

$$\widehat{\alpha}_{it} = Y_{it} - \sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} Y_{jt}$$

is an unbiased estimate for α_{it} for $t = T_0 + 1, \dots, T$. Based on this result, we can construct synthetic controls by solving Eq. (3). A solution to (3) can be obtained only if $(Y_{i1}, \dots, Y_{iT_0}, \boldsymbol{Z}_i')$ belongs to the convex hull of $\{(Y_{j1}, \dots, Y_{jT_0}, \boldsymbol{Z}_j'), j \in \mathcal{N}\}$. This is often not true in practice. Consequently, we construct $\boldsymbol{w}^{(i)}$ such that Eq. (3) holds approximately. The algorithm for approximating Eq. (3) is discussed in Section 4.2. In cases where $(Y_{i1}, \dots, Y_{iT_0}, \boldsymbol{Z}_i')$ falls far from the convex hull of $\{(Y_{j1}, \dots, Y_{jT_0}, \boldsymbol{Z}_j'), j \in \mathcal{N}\}$, it is not possible to even obtain $\boldsymbol{w}^{(i)}$ such that Eq. (3) holds approximately. In these cases, there would be relatively large discrepancy between Y_{it} and $\sum_{j\in\mathcal{N}} w_j^{(i)} Y_{jt}$ for $t \in \{1, \dots, T_0\}$, and this discrepancy can be computed and visualized. With this natural diagnostic mechanism, we would know if synthetic controls do not match the affected routes well.

4.2. Implementation

In this section, we describe our procedure to approximate Eq. (3) and the algorithm for constructing synthetic controls. Let the T_0-dimensional vector $\boldsymbol{k} = (k_1, \dots, k_{T_0})'$ be a linear combination of pre-ETS outcomes: $\bar{Y}_i^{\boldsymbol{k}} = \sum_{s=1}^{T_0} k_s Y_{is}$, where $i \in \mathcal{I}$. For example, if $k_1 = \cdots = k_{T_0-1} = 0$ and $k_{T_0} = 1$, then $\bar{Y}_i^{\boldsymbol{k}} = Y_{iT_0}$, the value of the outcome variable in the time period immediately prior to the ETS intervention. If $k_1 = \cdots = k_{T_0} = 1/T_0$, then $\bar{Y}_i^{\boldsymbol{k}} = T_0^{-1} \sum_{s=1}^{T_0} Y_{is}$, the simple average of the outcome variable for the pre-ETS periods. Consider M such linear combinations defined by vectors $\boldsymbol{k}_1, \ldots, \boldsymbol{k}_M$. Let $\boldsymbol{X}_i = (\boldsymbol{Z}_i', \bar{Y}_i^{\boldsymbol{k}_1}, \ldots, \bar{Y}_i^{\boldsymbol{k}_M})'$ be a k-dimensional ($k = r + M$) vector of pre-ETS characteristics for the affected route. Similarly, define a $k \times J$ matrix $\boldsymbol{X}_0$ whose jth column is $(\boldsymbol{Z}_j', \bar{Y}_j^{\boldsymbol{k}_1}, \ldots, \bar{Y}_j^{\boldsymbol{k}_M})'$, i.e., the same variables for the jth unaffected route for $j = 1, \ldots, J$. In order for Eq. (3) to hold approximately, we consider the weight vector that minimizes

$$\left\| \boldsymbol{X}_i - \boldsymbol{X}_0 \boldsymbol{w}^{(i)} \right\|_V^2 = \left(\boldsymbol{X}_i - \boldsymbol{X}_0 \boldsymbol{w}^{(i)} \right)' \boldsymbol{V} \left(\boldsymbol{X}_i - \boldsymbol{X}_0 \boldsymbol{w}^{(i)} \right), \tag{4}$$
$$\text{subject to } \sum_{j \in \mathcal{N}} w_j^{(i)} = 1, \text{ and } w_j^{(i)} \geq 0, \ j \in \mathcal{N},$$

where $\boldsymbol{V}$ is some positive semidefinite matrix. Denote the solution to (4) by $\boldsymbol{w}^{(i)}(\boldsymbol{V})$. Next, following the suggestion given in Abadie et al. (2010), we choose $\boldsymbol{V}$ among positive definite diagonal matrices such that the residual sum of squares (RSS) of the outcome variable is minimized for the pre-ETS periods. That is, choose $\boldsymbol{V}$ by solving

$$\min_{\boldsymbol{V} \in \mathbb{V}} \text{RSS}(\boldsymbol{V}) = \sum_{t=1}^{T_0} \left(Y_{it} - \sum_{j \in \mathcal{N}} \widetilde{w}_j^{(i)}(\boldsymbol{V}) Y_{jt} \right)^2, \tag{5}$$

where $\mathbb{V}$ denotes the set of all positive definite diagonal matrices. Denote $\boldsymbol{V}^*$ the solution to (5) and the weight vector $\widetilde{\boldsymbol{w}}^{(i)}$ for the synthetic control given by Eq. (3) is approximated by $\boldsymbol{w}^{(i)}(\boldsymbol{V}^*)$. Thus, $\widetilde{\boldsymbol{w}}^{(i)}$ is obtained by solving the nested minimization problem (4)–(5). In our implementation, we apply both the simplex algorithm in Nelder and Mead (1965) and the quasi-Newton method in Fletcher (2013) and the result with the smaller RSS value is returned (see Abadie et al. 2011 for more details). In our ETS study, $\boldsymbol{X}_i$ is chosen to be the 8-dimensional variable that includes the route distance, population and per capita GDP of the departure country averaged over the pre-ETS period, population and per capita GDP of the arrival country averaged over the pre-ETS period, and outcomes (i.e., seats or size) observed in 2007, 2009 and 2011.

The nested minimization problem needs to be solved for each route affected by the ETS policy. In our seats analysis sample, there are 53,566 affected routes and 18,542 unaffected routes, so the dimension of the minimization problem is high and needs to be done 53,566 times. Such computational undertaking consumes tremendous amount of computing resources and can become infeasible. To address this issue, we adopt a stochastic approximation scheme, described below.

Stochastic Approximation Scheme

For each $i \in \mathcal{I}$, do the following:

1. Randomly sample J_0 ($1 \leq J_0 < J$) unaffected routes from $\mathcal{N}$, and call this subset of unaffected routes $\mathcal{N}_0$.
2. Solve the nested minimization problem (4)–(5) with $\mathcal{N}_0$ substituting for $\mathcal{N}$.
3. Repeat the previous two steps R times and return the vector weight with the smallest RSS.

$J_0 (< J)$ reduces the dimension of the nested minimization problem and repeating the sampling multiple times mitigates the risk of being trapped in local minima. We have found in our numerical experiments that setting $J_0 = 20$ and $R = 100$ gives stable results and further increasing the values of J_0 or R results in little improvement. In our reporting of the final results, J_0 is chosen to be 40 and R is chosen to be 200.

5. Data

5.1. Carrier-route data

We examined annual data on all flights within Europe at the carrier-route level over the period of 2007–2017, which covers the time periods before and after the implementation of the EU ETS. We obtained our data from the air travel intelligence company Official Airline Guide (OAG), the host of the world's largest network of airline data. Our sample has 793,188 airline-route observations in a panel dataset. For each observation, the dataset includes the total number of seats, flight frequency, departure and arrival airports, and operating airline on a yearly basis. It should be noted that more comprehensive results could have been obtained if airfare price data were available for our analysis, as the trend of average airfare for each route is critical to understand airlines' pricing strategies in parallel with flight frequency decisions. It is also worth pointing out that the absence of the price data would not affect the validity of our results. On a side note, other relevant studies on the impacts of the EU ETS on aviation (e.g., Heiaas 2021, Fageda and Teixidó 2022) did not cover airfare price, also likely due to the unavailability of the data.

Routes affected by the EU ETS are those with both origin and destination in the European Economic Area (EEA), which includes EU28, Liechtenstein, Iceland and Norway (European Parliament and of the Council 2008). Routes with either origin or destination (or both) in non-EEA countries form the pool of control observations, from which synthetic controls are constructed to produce the counterfactual outcome trajectories. The European non-EEA countries are Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Faroe Islands, Georgia, Gibraltar, Macedonia, Montenegro, Republic of Moldova, Russia, Serbia, Switzerland, Turkey, and Ukraine. In our sample, there are 203,962 control airline-route observations, and the remaining 589,266 observations are those affected by the EU ETS.

We perform two analyses with our sample: *Seats Analysis* and *Size Analysis*. In Seats Analysis, the outcome variable Y_{it} is the annual total number of seats for a particular carrier on a specific route. This analysis evaluates the impact of the EU ETS on the

Table 1
Descriptive statistics of the annual total number of seats and aircraft size. The rows of *mean* and *sd* are averages and standard deviations respectively.

Analysis	EU ETS	Statistics	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Seats	Yes	mean	15525	15973	15093	15549	16122	16439	16507	16980	17887	19068	19878
		sd	53373	52418	49917	50901	51632	52305	51963	52505	54159	55572	55982
	No	mean	11549	12651	13159	13712	15067	16421	18366	20406	22361	23427	24382
		sd	40841	42485	42851	44364	47321	51349	55035	57817	61422	63270	66966
Size	Yes	mean	138	139	139	140	142	142	145	146	148	149	151
		sd	51.0	50.0	50.2	49.8	50.0	48.0	48.7	48.3	48.2	48.6	48.6
	No	mean	133	135	137	137	137	137	141	142	143	148	152
		sd	37.1	35.8	35.7	34.8	37.0	35.2	37.4	37.4	38.1	37.9	38.5

Table 2
Descriptive statistics of the control variables in Seats and Size Analyses. The rows of *mean* and *sd* are averages and standard deviations respectively. GDP_{Dep}, GDP_{Arr}, POP_{Dep}, and POP_{Arr} denotes the per capita GDP of the departure country, the per capita GDP of the arrival country, the population of the departure country, and the population of the arrival country, respectively. The columns of POP_{Dep}, and POP_{Arr} are in the unit of 10^7.

Analysis	EU ETS	Statistics	GDP_{Dep}	GDP_{Arr}	POP_{Dep}	POP_{Arr}	HD	HHI
Seats	Yes	mean	38030	38018	4.31	4.30	1230	
		sd	15960	15966	2.75	2.75	808	
	No	mean	27722	27845	5.73	5.71	1462	
		sd	24642	24721	4.61	4.61	831	
Size	Yes	mean	41089	41115	4.19	4.18	1175	0.736
		sd	19107	19117	2.81	2.81	779	0.272
	No	mean	29377	29390	5.30	5.29	1332	0.737
		sd	25751	25806	4.51	4.52	747	0.252

supply of flights. In Size Analysis, the outcome variable Y_{it} is the annual average aircraft size, defined by the ratio of the total number of seats to the flight frequency. This analysis assesses airlines' responses to the EU ETS by measuring their adjustments made to the aircraft sizes. Some airlines stopped flying certain routes for some time during 2007–2017. In such cases, the number of seats and frequency are both zero, so the size (i.e., total number of seats/frequency) becomes ill-defined. As a result, our Size Analysis is restricted to cases that have positive number of seats throughout the entire period of 2007–2017. In this smaller sample, there are 12,969 control observations and 54,560 affected observations. The descriptive statistics of the number of seats and the average size are shown in Table 1.

5.2. Control variables

Since the supply of flights on a specific route is affected by the characteristics of the departure and arrival regions, it is necessary to control for variables that may confound the EU ETS effect. In the literature, the gravity model (Zhang et al., 2018) has suggested that the air traffic between two regions depends on the economic and demographic size of each region and the distance between them. Consequently, we consider the population and per capita GDP (in current U.S. dollars) of both origin and destination countries during the period of 2007–2017. Data are obtained from the World Bank database, *DataBank*. Regarding the distance between two airports, we compute their haversine distance (Van Brummelen, 2012) using the airports' longitudes and latitudes. The use of haversine distance (HD) has been widely documented in the navigation and trigonometric literature (e.g., Goodwin 1910, Sheppard 1922, Hedrick 1913). The longitude–latitude data are obtained from the OpenFlights database (https://openflights.org/data.html). There are 29 airports missing from the OpenFlights database. We obtained these data from the website https://airports-list.com/airport. In addition to these five variables, we also include the Herfindahl–Hirschman Index (HHI), a commonly accepted measure of market concentration, as a control variable. For some routes, all airlines stopped flying them for some time in the period of 2007–2017. In these situations, HHI cannot be calculated. We still want to keep these routes in our analysis, since those airlines' decision to stop flying them may be the result of EU ETS. This issue is especially relevant to our Seats Analysis. We do not have this issue with the smaller sample for Size Analysis, which only includes routes with positive flight frequency throughout the entire period. Therefore, HHI is used in Size Analysis as a control variable, but not in Seats Analysis. Some descriptive statistics of these control variables are presented in Table 2.

Applying model (1) to our sample, for the ith carrier-route observation, we define $\boldsymbol{Z}_i$ to be the following 5 variables: the haversine distance between the departure and arrival airports, the population of the departure and arrival country, and the per capita GDP of the departure and arrival country. Population and per capita GDP are averaged over the pre-ETS period 2007–2011. In Size Analysis, $\boldsymbol{Z}_i$ also includes HHI.

5.3. Segmentation variables

Since our matching with synthetic controls is done at the most granular level (i.e., the carrier-route observation level), the results of our analysis can be viewed on aggregated or segmented levels. Different segmentations enable analysis of the EU ETS impact on

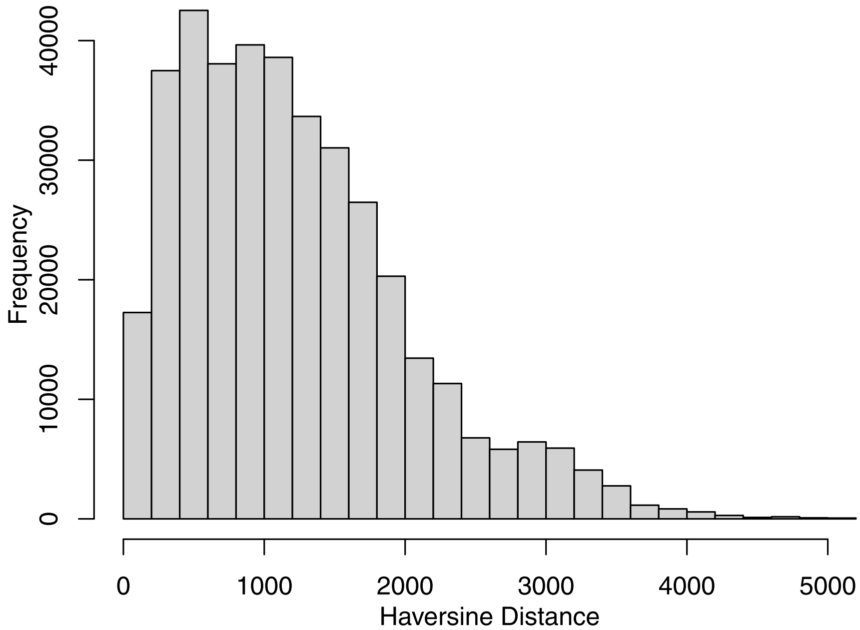

Fig. 1. Histogram of the haversine distances.

different segments of the aviation market. We consider three different segmentations based on the following variables: carrier type (flag, regional, vs. low-cost), transport topology (spoke routes vs. hub routes), and flight length (short hauls vs. medium/long hauls). Data for these segmentation variables are obtained from various websites. Flag carriers are historically associated with their home country and often enjoy preferential rights by the government, consequently, these carriers are relatively easy to identify via web searches. The ICAO has published a list of low-cost carriers, and the European Regional Airline Association (ERA) provides a list of EU regional carriers. We have used these two lists to establish the categories of low-cost and regional carriers. Regarding transport topology, we obtained data from the Wikipedia page https://en.wikipedia.org/wiki/List_of_hub_airports. As for flight length, the European Organization for the Safety of Air Navigation, commonly known as Eurocontrol, defines short-haul, medium-haul and long-haul routes using the cutoffs 1,500 km and 4,000 km for flight length (Eurocontrol, 2011)[7]. This convention is based on all global flight routes including intercontinental flights. In our dataset, however, all the flight routes are within Europe, so there are very few observations that can be classified as long-haul routes by Eurocontrol's definition. Fig. 1 shows a histogram of all the haversine distances of routes affected by the EU ETS. The median and 75% quantile value of the haversine distances is 1,089.16 km and 1,676.57 km, respectively. Thus, the majority of routes in our sample will be classified as short hauls if we adopt Eurocontrol's convention. In order to have a relatively balanced segmentation based on flight length, we decided not to adopt Eurocontrol's convention and classify a route as short-haul if its haversine distance is less than 500 km. In addition, we combine medium- and long-hauls into one category. The breakdown of proportions of these segments are shown in Table 3.

6. Results

6.1. Total seat capacity

We first investigate the impact of the EU ETS on the total seat capacity of airlines. From Fig. 2, we can clearly see that the EU ETS had a significant effect in terms of magnitude and percentage. In particular, without the EU ETS, there should have been a substantial increase in the total seat capacity for the airlines between 2011 and 2017 (blue dash line). However, the real increase

[7] Stage length is important since it affects fleet composition (i.e., size), airlines' costs and profitability and, thus, airlines' strategic behavior. Wei and Hansen (2003) find that economies of aircraft size and stage length exist and that for any given stage length there is an optimal size, which increases with stage length. However, the scale properties of the cost function are changed considerably if pilot unit cost is treated as endogenous, since it is correlated with size. The cost-minimizing aircraft size is therefore considerably smaller, particularly at short stage lengths, when pilot cost is treated as endogenous, and this helps to explain why US airlines expect to accommodate future traffic growth with more flights instead of larger planes. Second, longer flights burn less fuel per Available Seat Mile (ASM). The reason for this is the fact that the takeoff and landing phases of flight use the most fuel per ASM. Therefore, the longer the flight, the more fuel-efficient ASMs there are to dilute the less efficient takeoff and landing phases (Vasigh et al. 2018). It was also found that airlines with longer routes can achieve higher daily aircraft flight hours. The negative correlation between operating expenses and the daily aircraft flight hours most likely reflects the fact that airlines flying longer routes have higher daily utilization rates and also achieve lower costs per ASM due to the larger size of aircraft (Seristö and Vepsäläinen 1997).

Table 3
The proportions of different segments in the sample.

Analysis	EU ETS	Carrier type			Flight distance		Transport topology	
		Flag	Regional	Low cost	Short	Medium/Long	Spoke	Hub
Seats	Yes	0.252	0.072	0.676	0.209	0.791	0.872	0.128
	No	0.447	0.081	0.472	0.121	0.879	0.830	0.170
Size	Yes	0.427	0.065	0.508	0.215	0.785	0.607	0.393
	No	0.817	0.014	0.169	0.137	0.823	0.437	0.563

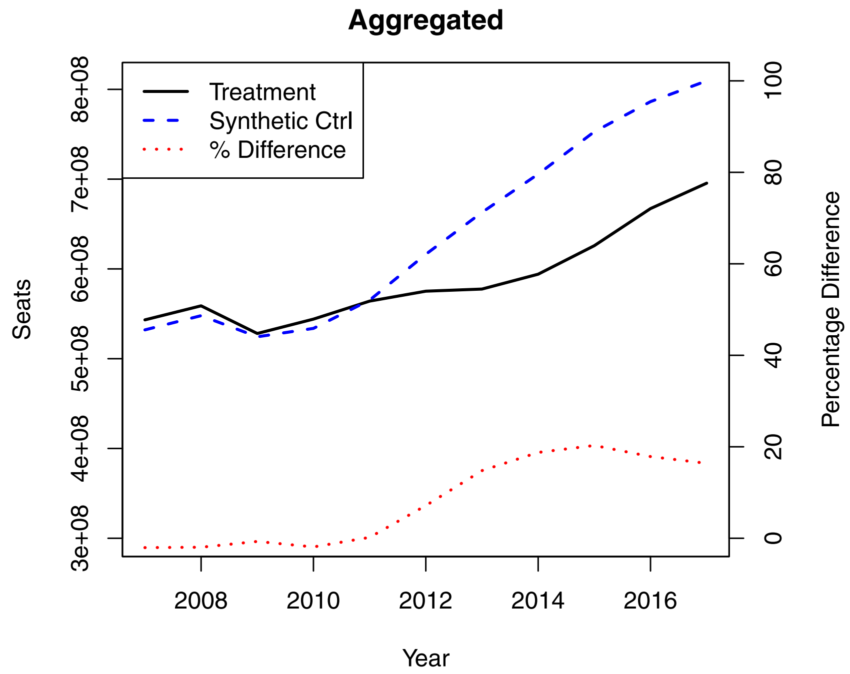

Fig. 2. Total number of seats at the aggregated level.

was much smaller with the EU ETS in place (black line). Moreover, our analysis reveals that the EU ETS has caused a reduction of total airline seat capacity, and the magnitude of such reduction increases over time, at least in the first few years of implementation (the red dot line). The percentage of reduction can reach above 20% at its peak. This result is somewhat expected, but it has a very important policy implication, i.e., the ETS can indeed effectively suppress the airline seat capacity, while the impact is substantial after 2013. Another interesting observation from Fig. 2 is that after 2015, the seat capacity reduction percentage seems to reach a plateau and even decrease slightly. This may be caused by the fact that some of the airline seat capacity is not easily adjustable in the short term, and can take up to a few years for the full impact of the ETS to appear and stabilize. We need a longer panel to see whether this effect stabilizes at about 20%. It can also be seen from this figure that our synthetic control trajectory tracks the realized outcomes quite well during the pre-ETS period. Notably, in our model calibration, the synthetic weights $\boldsymbol{w}^{(i)}$ obtained from Eq. (4) do not make use of the realized outcomes in 2008 and 2010. Therefore, the approximation of synthetic controls to the observed outcomes in those two years can be regarded as an out-of-sample test. Our synthetic controls still approximate the observed outcomes well in those two years. This is evidence that the synthetic controls would be able to reproduce the trajectory of the actual outcomes had there been no ETS intervention, suggesting that our use of GDP, population and distance as control variables captures the air traffic dynamic between two regions reasonably well. This also empirically confirms the findings of the gravity model (e.g., Zhang et al. 2018) in the aviation research literature.

Next, we try to break down the impact of the EU ETS on airlines' total seat capacity according to various factors. The first factor is the business models of airlines. The three business models that we investigate are flag carriers (i.e., full-service carriers), low-cost carriers and regional carriers. From Fig. 3, we can see that the three business models generally show a similar pattern. However, each business model also has some distinctive features. In particular, the percentage reduction of flag carriers' seat capacity flattens after 2014, but still sees a modest increase till 2017, the end of our study period. On the contrary, the percentage reductions of low-cost carriers' and regional carriers' seat capacities reach a peak in 2015 and then take a downward trend. This is likely due to the fact that the EU ETS effectively increases the operating costs of airlines, and low-cost carriers and regional carriers are more cost sensitive than flag carriers. Furthermore, compared with flag carriers, these two types of airlines usually have a higher level of

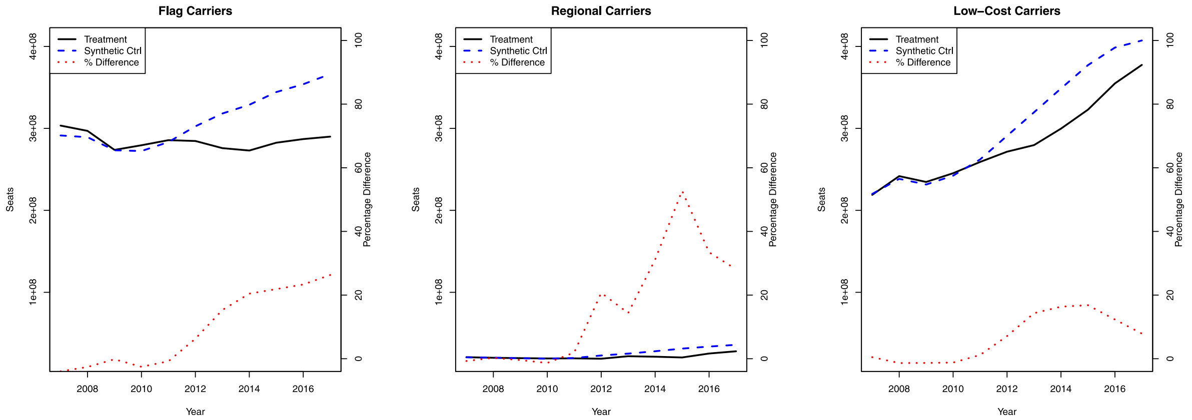

Fig. 3. Total number of seats by different types of carriers.

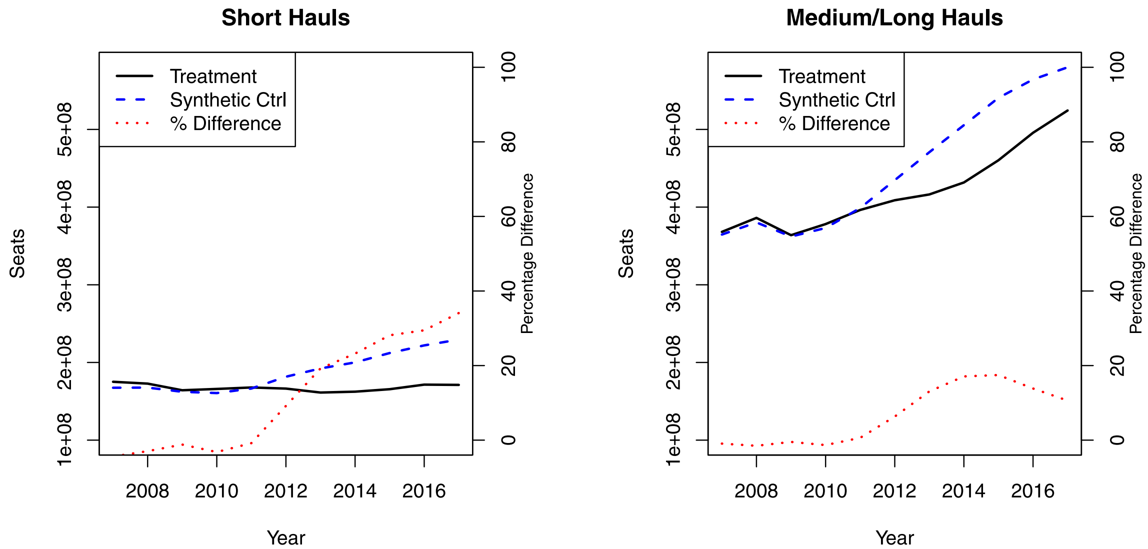

Fig. 4. Total number of seats by different flight lengths.

flexibility in adjusting their seat capacities, due to the fact that they usually operate smaller aircraft and have a higher percentage of their aircraft leased instead of owned.

The second factor is the length of haul. In particular, different origin–destination (OD) markets can be classified into either short-haul or long/medium-haul. It is obvious that the general pattern that the EU ETS reduces airlines' total seat capacity persists for both types of markets (see Fig. 4). However, in terms of the percentage of reduction, there is a large divergence. The short-haul markets have seen a substantial reduction in total seat capacity, reaching almost 40% in 2017, and the downward trend seems to continue. Comparatively speaking, the decrease in the total seat capacity in the long/medium-haul markets is much milder, peaking at about 20% in 2015 and slightly decreasing after. This is likely caused by two reasons: (i) medium/long-haul markets are more fuel and emission efficient, as take-off and landing account for disproportionally high percentages of fuel burn during a flight, and (ii) medium/long-haul markets have lower price sensitivities, because there are fewer substitutes. The airlines, therefore, can pass on the additional cost associated with the EU ETS on to the passengers more easily. This result also suggests that the EU ETS has achieved favorable policy outcomes. From an emission perspective, short-haul flight is indeed much less efficient as a means of fulfilling travel demand. Therefore, the EU ETS is supposed to have a larger negative impact on the short-haul markets than on the medium/long-haul markets.

The last factor to serve as a criterion to break down the impact of the EU ETS is the status of the origin and destination airports. We divided the OD markets into two groups, depending on whether one of the airports involved was a hub airport of the operating airline. From Fig. 5, we can see the general pattern that the EU ETS reduces airlines' total seat capacity for both types of markets. However, the impact on the spoke–spoke markets is clearly stronger than that on the markets involving at least one hub airport. This occurs because most of the spoke–spoke markets are smaller and are thereby served by small regional aircraft (e.g., Gillen et al.

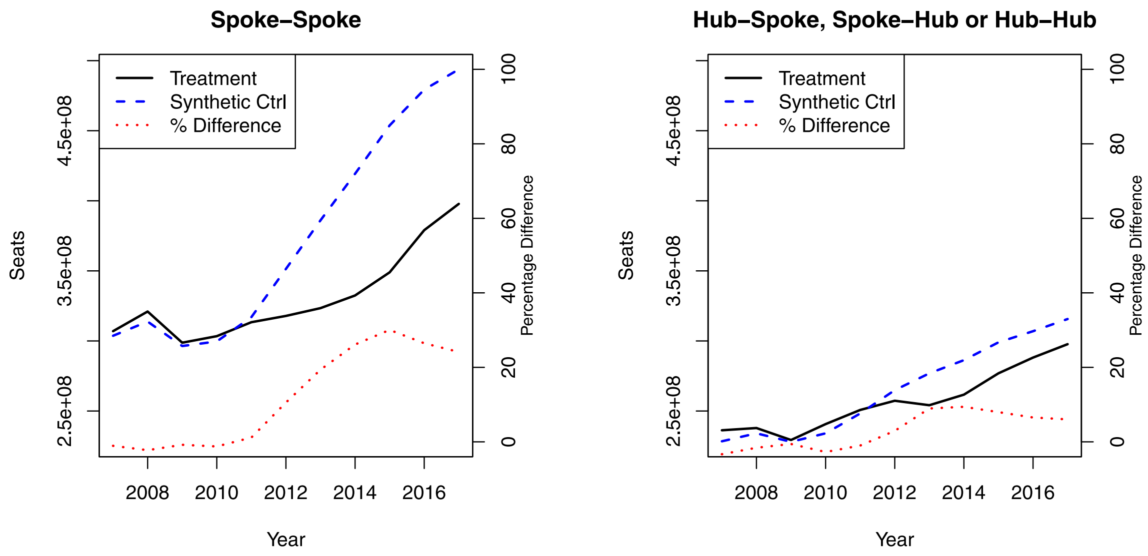

Fig. 5. Total number of seats by different transport topologies.

(2015)), which are less fuel and emission efficient. Naturally these markets would be more prone to the impacts of the EU ETS. The policy implications of this result are less straightforward. Although the spoke–spoke markets generally have lower demand, meaning that the negative impact of the EU ETS on the traffic in these markets may not affect the majority of the population, people affected may be in a demographic with a lower level of mobility. The EU ETS may cause a further reduction in their mobility resulting in a decrease in social fairness. With air travel harder to obtain, residents in the spoke cities may need to rely on other transport modes such as the automobile, which can be more environmentally detrimental from a per passenger perspective. However, cleaner transport alternatives such as high-speed rail may also exist in such markets. This result suggests that the overall welfare implications of the EU ETS may in fact be more complicated and require a more detailed analysis.

6.2. Aircraft size

Next, we looked into whether the EU ETS affected the longer-term decisions of the airlines. In particular, we studied whether the sizes of the aircraft operated by the airlines have been changed by the EU ETS. As discussed above, larger aircraft are generally more fuel and emission efficient than smaller aircraft from a per seat perspective. However, there are two issues worth noting. First, aircraft fuel efficiency is determined by many different factors, with size being only one of them. If the average size of the aircraft stays constant or even decreases, it may not necessarily mean that the average fuel efficiency of the aircraft is unchanged or lower, because newer generations of aircraft also tend to have better fuel efficiency. Second, aircraft size is a long-term decision variable, and it is more difficult for some airlines to adjust this variable. This is not to suggest that changes in aircraft size will not occur in response to the EU ETS, but rather it will likely be a more gradual process. From Fig. 6, it is clear that the EU ETS does not have a substantial impact on the average aircraft size. However, due to the reasons discussed above, this result is worth further analysis.

In terms of different business models of airlines, Fig. 7 shows that flag carriers and low-cost carriers present the same pattern as the general pattern in Fig. 6. However, the average size of aircraft operated by regional carriers has actually decreased after the implementation of the EU ETS. This seemingly counter-intuitive result may be due to the fact that regional carriers tend to serve thin markets in the first place. For major airlines including both flag carriers and low-cost carriers, a reduction of the total seat capacity can be achieved by decreasing the service frequency. This is not the case for regional carriers, as their service frequency was already low before the EU ETS due to lower demand, and a further reduction will lead to a substantial loss of the attractiveness and competitiveness of their service. In order to maintain a reasonable level of load factor, the only option these carriers have is to operate even smaller aircraft. This result further confirms that not all consequences of the EU ETS are desirable. If it holds true that smaller aircraft are less emission efficient on a per passenger level, the implementation of the EU ETS in fact induces the regional carriers to obtain an even higher per passenger emission. To counter this negative effect, when regional carriers change the aircraft in response to the EU ETS, they most likely would not only opt for smaller aircraft but also shift to more fuel-efficient product. What has become clear, however, is that the effect of the EU ETS on the per passenger emission level of regional carriers is not straightforward and needs deeper analysis.

In terms of different OD markets, the results are also consistent with the results for airline type. In particular, the average size of aircraft operated in the medium/long haul markets is not significantly affected by the EU ETS (see Fig. 8). However, we can see a small decrease in the average aircraft size in the short-haul markets. Similar patterns also exist based on the types of airports (see Fig. 9). In particular, for markets with at least one of the OD pair being a hub airport, the average aircraft size stays unchanged after

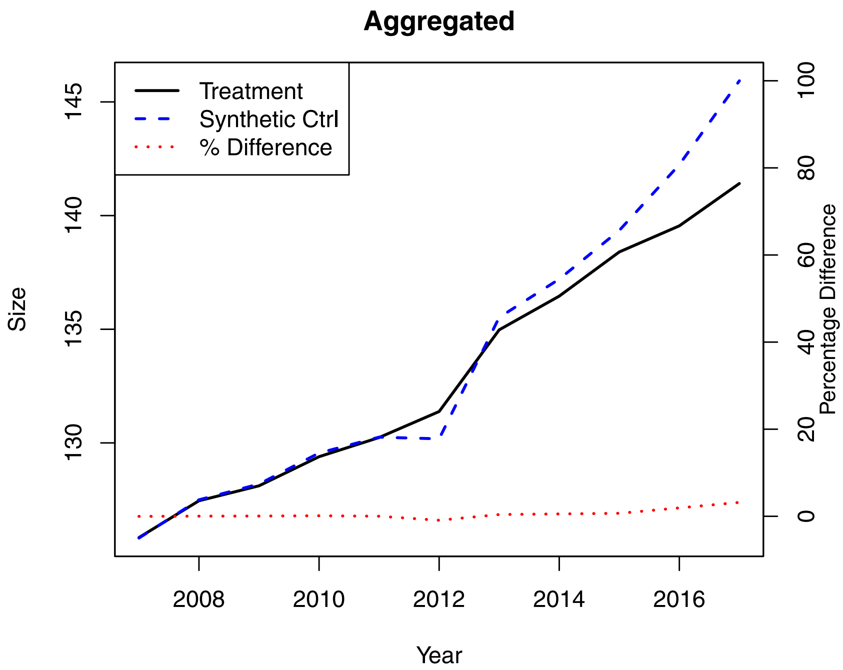

Fig. 6. Average aircraft size at the aggregated level.

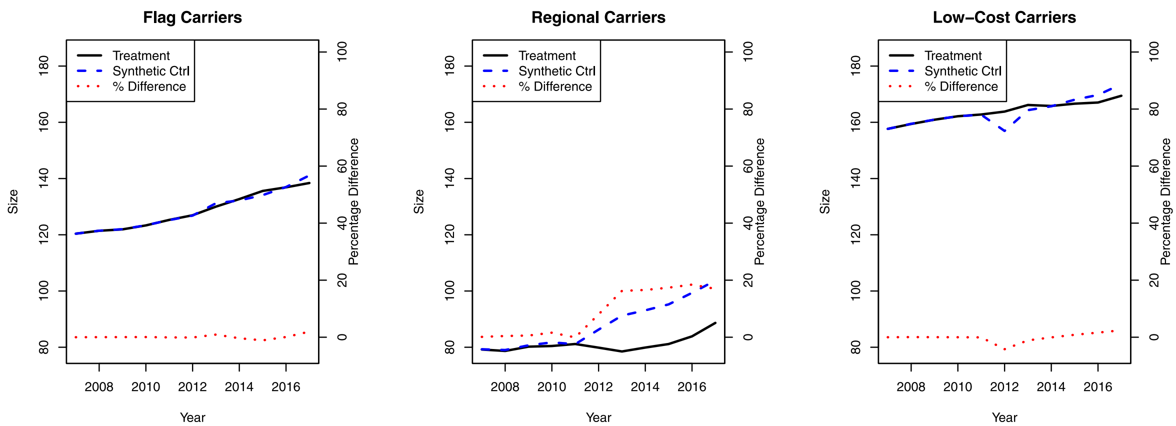

Fig. 7. Average aircraft size by different types of carriers.

the implementation of the EU ETS. For the spoke–spoke markets, the average aircraft size decreases slightly. These two results are consistent with the reduction of the average size of aircraft operated by regional carriers, as there should be a high level of overlap among these three types of markets. What our results suggest, is that the thinner short-haul spoke-to-spoke regional markets are affected the most and need to be carefully evaluated to assess the overall influences of the EU ETS and any ETS-like systems in the future.

Finally, similar considerations apply to the segmentation analysis based on HHI (monopolistic vs. non-monopolistic routes). In particular, for non-monopolistic markets, the average aircraft size stays unchanged after the implementation of the EU ETS (see Fig. 10), whereas in the monopolistic markets, the average aircraft size decreases slightly.

7. Concluding remarks

In this paper, we developed a novel application of the synthetic control method proposed by Abadie et al. (2010) to evaluate the causal impact of carbon pricing on aviation supply in response to the policy change in the EU ETS, the first large greenhouse gas emissions trading scheme in the world. Carbon pricing, whether delivered by means of carbon taxes or cap-and-trade systems, is expected to reduce emissions as a result of its impact on the marginal costs of affected industry players.

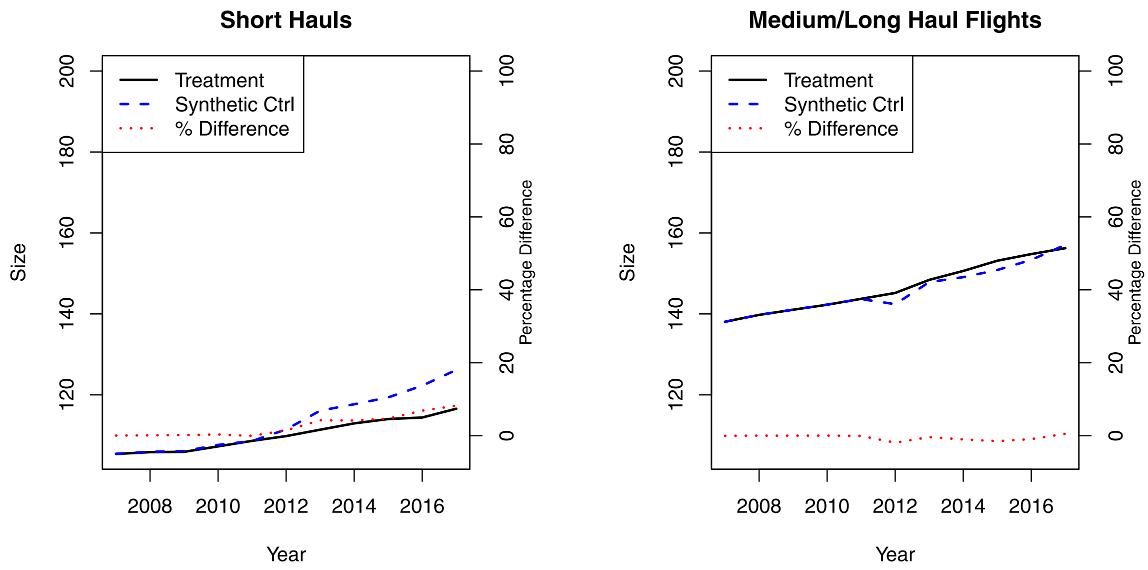

Fig. 8. Average aircraft size by different flight lengths.

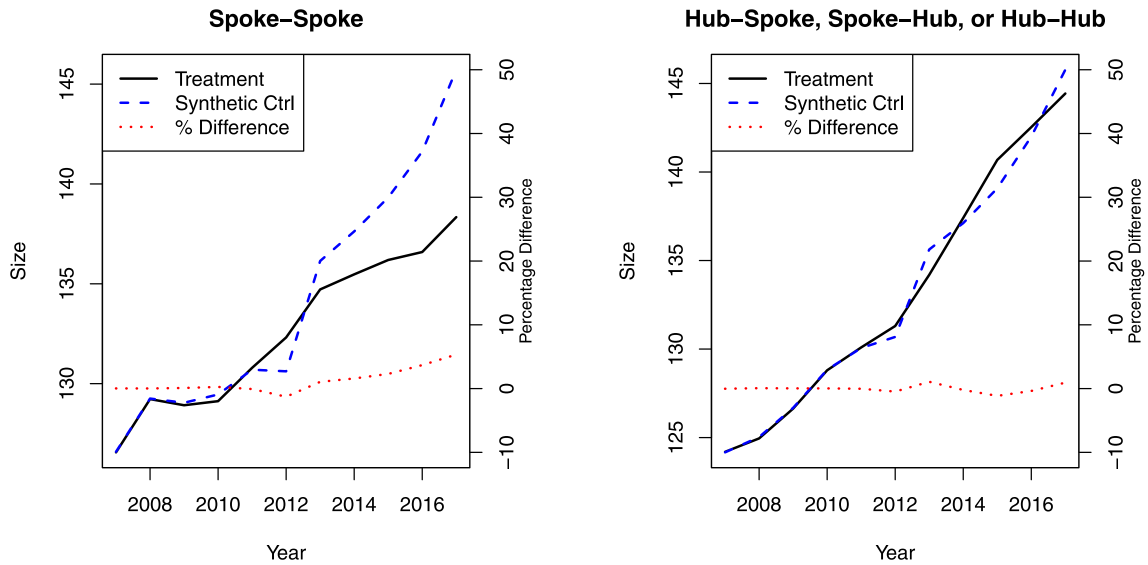

Fig. 9. Average aircraft size by different transport topologies.

Overall, we found that the EU ETS has had a relevant impact on containing the growth of air services within the European Economic Area, despite the fact that the measures applied to airlines are relatively soft with approximately half the allowances received being free. The overall effect of the policy has a remarkable impact on low-cost and regional airlines, which constitute about half of the European air traffic. The impact is also particularly notable on short-haul routes, spoke–spoke markets and monopolistic routes.

Our results have important policy implications and raise avenues for future research. The analysis shows that the EU ETS has caused a reduction of total airline seat capacity, while it does not have a substantial impact on the average aircraft size. We can conclude that the EU ETS has caused a reduction of total airline frequency. Our results empirically confirm theoretical predictions in Brueckner and Zhang (2010) that emission charges will reduce flight frequency, increase load factors while having no effect on aircraft size. It is important to note that our analysis only included data to the end of 2017. Further data collection is required to assess whether the EU ETS policy effect persists beyond 2017. From a policy perspective, the finding that airlines respond strongly on short-haul routes suggests that investments, at both the national and international level, to improve connectivity by rail (i.e., high-speed rail lines) should be seen as complementary measures to the EU ETS scheme to reduce emissions (D'Alfonso et al. 2015, 2016). Although carbon pricing alone may not be enough to deal with climate change, the evidence reported here suggests that

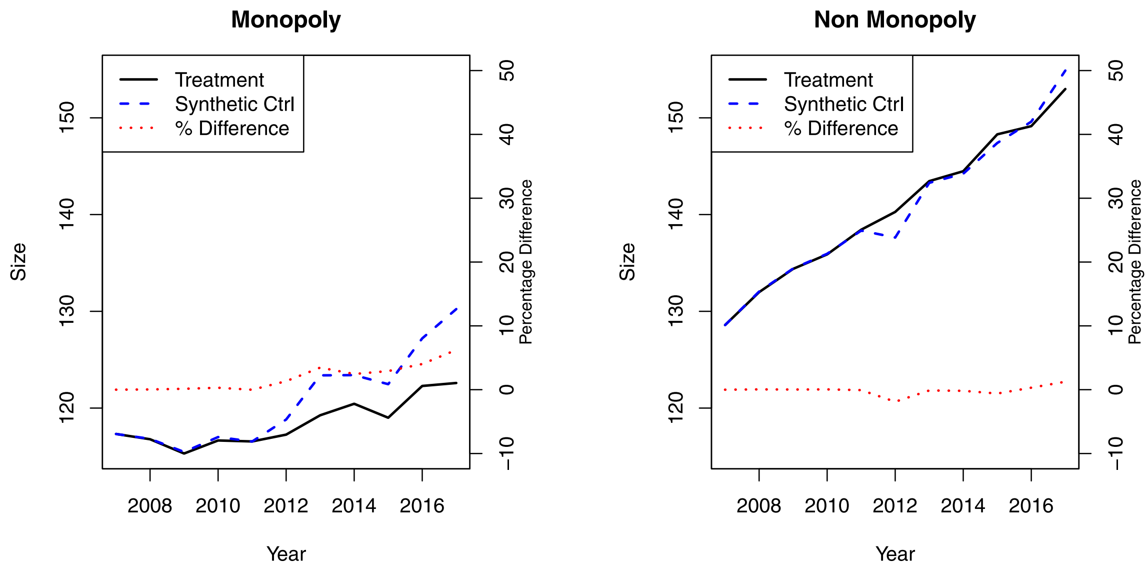

Fig. 10. Average aircraft size by different market conditions.

tougher measures to increase the price of carbon may be effective in achieving a reduction in emissions in the aviation sector. Demand-supply interaction allows us to signal that the reduction in supply has been accompanied by a reduction in demand and an increase in prices. Further research and data collection must seek to assess the impact of the EU ETS on passenger numbers and air fares. From a methodological perspective, although our stochastic approximation scheme makes the computational task manageable, it adds stochastic nature to the final results. If we can reasonably cluster the routes based on their characteristics, then the unaffected routes can be replaced by the corresponding clusters and the amount of computation would be dramatically reduced. This is certainly an interesting direction to pursue in future research.

Acknowledgment

This research is supported by the Research Center for Environment and Sustainable Development of the China Civil Aviation.

Appendix

Computational run time for seats analysis

Our stochastic approximation scheme aims to reduce the computation needed to solve the nested optimization (4)–(5). Solving the optimization with the entire set of unaffected routes is extremely time consuming. In this section, we present some numerical results for comparing the run time of our approximation scheme versus fully solving the nested optimization. We focus on the Seats Analysis only. The column denoted by *One Route* in Table 4 shows the run time of solving (4)–(5) for one affected route in various scenarios. The total run time (i.e., the *Total* column) then is estimated by multiplying the one-route run time by 53,566 (the sample size of the affected routes) and divided by the number of CPUs (assumed to be 100) in a parallel computing setting. We consider $R = 100$, 200 and $J_0 = 10$, 20, and 40 in Table 4 for the proposed stochastic approximation scheme. Fully solving the optimization amounts to setting $R = 1$ and $J_0 = J = 18542$ (the sample size of the unaffected routes). In addition, we also consider the cases where $J_0 = J/2$ and $J_0 = J/4$ in order to gauge the time reduction by shrinking the value of J_0. It can be seen from the table that the run time is much longer when J_0 is large. In particular, it takes almost 5 years to fully solve the optimization for our Seats Analysis. The code is written in R (R. Core Team, 2022) and run on a Linux Centos 7 machine with Intel Core i7-6950X 4.0 GHz CPUs.

Proof of Proposition 1. It follows from (1) that

$$\sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} Y_{jt} = \delta_t + \theta_t' \sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \boldsymbol{Z}_j + \lambda_t' \sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \boldsymbol{\mu}_j + \sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \varepsilon_{jt}, \tag{A.1}$$

$$Y_{it} = \delta_t + \theta_t' \boldsymbol{Z}_i + \lambda_t' \boldsymbol{\mu}_i + \varepsilon_{it}, \tag{A.2}$$

where $t = 1, \dots, T_0$. Subtracting (A.1) from (A.2), we have

$$0 = \lambda_t' \left(\sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \boldsymbol{\mu}_j - \boldsymbol{\mu}_i \right) + \sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \varepsilon_{jt} - \varepsilon_{it}, \quad t = 1, \dots, T_0. \tag{A.3}$$

Table 4
Computational run time comparison in Seats Analysis: the proposed stochastic approximation scheme versus fully solving the nested optimization (4) – (5). The code is written in R and run on a Linux Centos 7 machine with Intel Core i7-6950X 4.0 GHz CPUs.

R	Model size (i.e., J_0)	One route (in seconds)	Total (in days)
100	10	402.621	2.496
	20	582.533	3.612
	40	757.947	4.699
200	10	809.705	5.020
	20	1135.496	7.040
	40	1547.507	9.594
1	4635	20347.150	126.148
	9271	77483.182	480.378
	18542	268256.003	1663.125

Define $\boldsymbol{\varepsilon}_i = (\varepsilon_{i1}, \dots, \varepsilon_{iT_0})'$, $\boldsymbol{\varepsilon}_j = (\varepsilon_{j1}, \dots, \varepsilon_{jT_0})'$ for $j \in \mathcal{N}$, and $\boldsymbol{\Lambda} = (\lambda_1, \dots, \lambda_{T_0})'$ (of size $T_0 \times F$). Rewrite (A.3) in matrix notation.

$$\mathbf{0} = \boldsymbol{\Lambda}\left(\sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \boldsymbol{\mu}_j - \boldsymbol{\mu}_i\right) + \left(\sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \left(\boldsymbol{\varepsilon}_j - \boldsymbol{\varepsilon}_i\right)\right). \tag{A.4}$$

Multiplying both sides of (A.4) by $\boldsymbol{\Lambda}'$, we have

$$\boldsymbol{\mu}_i - \sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \boldsymbol{\mu}_j = \left(\boldsymbol{\Lambda}'\boldsymbol{\Lambda}\right)^{-1} \boldsymbol{\Lambda}' \left(\sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \left(\boldsymbol{\varepsilon}_j - \boldsymbol{\varepsilon}_i\right)\right).$$

Here $\boldsymbol{\Lambda}'\boldsymbol{\Lambda} = \sum_{t=1}^{T_0} \lambda_t \lambda_t'$ is invertible by assumption. It follows that

$$\mathrm{E}\left(\sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} Y_{jt} - Y_{it}^N\right) = \lambda_t' \mathrm{E}\left\{\sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \boldsymbol{\mu}_j - \boldsymbol{\mu}_i\right\} + \mathrm{E}\left\{\sum_{j\in\mathcal{N}} \widetilde{w}_j^{(i)} \varepsilon_{jt} - \varepsilon_{it}\right\} = 0,\ t = 1, \dots, T. \quad \square$$

References

Abadie, A., 2005. Semiparametric difference-in-differences estimators. Rev. Econom. Stud. 72 (1), 1–19.
Abadie, A., Diamond, A., Hainmueller, J., 2010. Synthetic control methods for comparative case studies: Estimating the effect of California's tobacco control program. J. Amer. Statist. Assoc. 105 (490), 493–505.
Abadie, A., Diamond, A., Hainmueller, J., 2011. Synth: An R package for synthetic control methods in comparative case studies. J. Stat. Softw. 42 (13).
Abadie, A., Diamond, A., Hainmueller, J., 2015. Comparative politics and the synthetic control method. Am. J. Political Sci. 59 (2), 495–510.
Abadie, A., Gardeazabal, J., 2003. The economic costs of conflict: A case study of the Basque Country. Amer. Econ. Rev. 93 (1), 113–132.
Albers, S., Bühne, J.-A., Peters, H., 2009. Will the EU ETS instigate airline network reconfigurations? J. Air Transp. Manag. 15 (1), 1–6.
Amankwah-Amoah, J., 2020. Stepping up and stepping out of COVID-19: New challenges for environmental sustainability policies in the global airline industry. J. Cleaner Prod. 271, 123000.
Anger, A., 2010. Including aviation in the European emissions trading scheme: Impacts on the industry, CO2 emissions and macroeconomic activity in the EU. J. Air Transp. Manag. 16 (2), 100–105.
Angrist, J.D., Pischke, J.-S., 2008. Mostly Harmless Econometrics: An Empiricist's Companion. Princeton University Press.
Bai, J., 2009. Panel data models with interactive fixed effects. Econometrica 77 (4), 1229–1279.
Bai, J., Ng, S., 2002. Determining the number of factors in approximate factor models. Econometrica 70 (1), 191–221.
Belobaba, P., 2009. The airline planning process. Glob. Airl. Ind. 153–181.
Brueckner, J.K., Czerny, A.I., Gaggero, A.A., 2021. Airline mitigation of propagated delays via schedule buffers: Theory and empirics. Transp. Res. Part E: Logist. Transp. Rev. 150, 102333.
Brueckner, J.K., Lin, M.H., 2016. Convenient flight connections vs. airport congestion: Modeling the 'rolling hub'. Int. J. Ind. Organ. 48, 118–142.
Brueckner, J.K., Zhang, A., 2010. Airline emission charges: Effects on airfares, service quality, and aircraft design. Transp. Res. B 44 (8–9), 960–971.
Card, D., 1990. The impact of theMariel boatlift on the Miami labor market. Indus. Labor Relations Rev. 43 (2), 245–257.
Connor, G., Korajczyk, R.A., 1986. Performance measurement with the arbitrage pricing theory: A new framework for analysis. J. Financ. Econ. 15 (3), 373–394.
D'Alfonso, T., Jiang, C., Bracaglia, V., 2015. Would competition between air transport and high-speed rail benefit environment and social welfare? Transp. Res. B 74, 118–137.
D'Alfonso, T., Jiang, C., Bracaglia, V., 2016. Air transport and high-speed rail competition: Environmental implications and mitigation strategies. Transp. Res. Part A: Policy Practice 92, 261–276.
Deeney, P., Cummins, M., Heintz, K., Pryce, M.T., 2021. A real options based decision support tool for R&D investment: Application to CO2 recycling technology. European J. Oper. Res. 289 (2), 696–711.
Derigs, U., Illing, S., 2013. Does EU ETS instigate Air Cargo network reconfiguration? A model-based analysis. European J. Oper. Res. 225 (3), 518–527.
Dou, G., Choi, T.-M., 2021. Does implementing trade-in and green technology together benefit the environment? European J. Oper. Res..
Eurocontrol, 2011. Study into the impact of the global economic crisis on airframe utilisation. Eurocontrol Library 21.
European Parliament and of the Council, 2008. Amending Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the community. Official J. Eur. Union Directive 2008/101/EC, 213–231.
European Union Aviation Safety Agency, 2019. European aviation environmental report. https://ec.europa.eu/transport/sites/transport/files/2019-aviation-environmental-report.pdf (Accessed 25 May 2021).

Fageda, X., Flores-Fillol, R., 2015. A note on optimal airline networks under airport congestion. Econom. Lett. 128, 90–94.
Fageda, X., Flores-Fillol, R., 2016. How do airlines react to airport congestion? The role of networks. Reg. Sci. Urban Econ. 56, 73–81.
Fageda, X., Teixidó, J.J., 2022. Pricing carbon in the aviation sector: Evidence from the European emissions trading system. J. Environ. Econ. Manag. 111, 102591.
Fletcher, R., 2013. Practical Methods of Optimization. John Wiley & Sons.
Flora, M., Vargiolu, T., 2020. Price dynamics in the European union Emissions Trading System and evaluation of its ability to boost emission-related investment decisions. European J. Oper. Res. 280 (1), 383–394.
Fowlie, M., Holland, S.P., Mansur, E.T., 2012. What do emissions markets deliver and to whom? Evidence from Southern California's NOx trading program. Amer. Econ. Rev. 102 (2), 965–993.
Fukui, H., Miyoshi, C., 2017. The impact of aviation fuel tax on fuel consumption and carbon emissions: The case of the US airline industry. Transp. Res. Part D: Transp. Environ. 50, 234–253.
Gillen, D., Hasheminia, H., Jiang, C., 2015. Strategic considerations behind the network–regional airline tie ups–a theoretical and empirical study. Transp. Res. B 72, 93–111.
Givoni, M., Rietveld, P., 2009. Airline's choice of aircraft size–Explanations and implications. Transp. Res. Part A: Policy and Practice 43 (5), 500–510.
Givoni, M., Rietveld, P., 2010. The environmental implications of airlines' choice of aircraft size. J. Air Transp. Manag. 16 (3), 159–167.
Goodwin, H., 1910. The haversine in nautical astronomy. US Naval Institute Proceedings 36 (3), 735–746.
Hedrick, E.R., 1913. Logarithmic and Trigonometric Tables. Macmillan.
Heiaas, A.M., 2021. The EU ETS and Aviation: Evaluating the effectiveness of the EU emission trading system in reducing emissions from air travel. Rev. Bus. Econ. Stud. 1.
Hepburn, C., Stern, N., Stiglitz, J.E., 2020. "Carbon pricing" special issue in the European economic review. Eur. Econ. Rev. 127, 103440.
Hofer, C., Dresner, M.E., Windle, R.J., 2010. The environmental effects of airline carbon emissions taxation in the US. Transp. Res. Part D: Transport Environ. 15 (1), 37–45.
Hu, R., Xiao, Y.-b., Jiang, C., 2018. Jet fuel hedging, operational fuel efficiency improvement and carbon tax. Transp. Res. B 116, 103–123.
International Civil Aviation Organization, 2019. ICAO - 2019 - Environmental report. https://www.icao.int/environmental-protection/Documents/ICAO-ENV-Report2019-F1-WEB%20(1).pdf (Accessed 25 May 2021).
Klemetsen, M., Rosendahl, K.E., Jakobsen, A.L., 2020. The impacts of the EU ETS on Norwegian plants' environmental and economic performance. Climate Change Economics 11 (01), 2050006.
Li, Y., Wang, Y.-z., Cui, Q., 2016. Has airline efficiency affected by the inclusion of aviation into European Union Emission Trading Scheme? Evidences from 22 airlines during 2008–2012. Energy 96, 8–22.
Liao, W., Fan, Y., Wang, C., 2022. How does COVID-19 affect the implementation of CORSIA? J. Air Transp. Manag. 102180.
Maertens, S., Grimme, W., Scheelhaase, J., Jung, M., 2019. Options to continue the EU ETS for Aviation in a CORSIA-world. Sustainability 11 (20), 5703.
Mai, D.T.T., 2021. Revising the EU ETS and CORSIA in times of the COVID-19 pandemic: challenges for reducing global aviation emissions. Climate Policy 21 (10), 1357–1367.
Malina, R., McConnachie, D., Winchester, N., Wollersheim, C., Paltsev, S., Waitz, I.A., 2012. The impact of the European Union emissions trading scheme on US aviation. J. Air Transp. Manag. 19, 36–41.
Morrell, P., 2007. An evaluation of possible EU air transport emissions trading scheme allocation methods. Energy Policy 35 (11), 5562–5570.
Nava, C.R., Meleo, L., Cassetta, E., Morelli, G., 2018. The impact of the EU ETS on the aviation sector: Competitive effects of abatement efforts by airlines. Transp. Res. Part A: Policy and Practice 113, 20–34.
Nelder, J.A., Mead, R., 1965. A simplex method for function minimization. Comput. J. 7 (4), 308–313.
R. Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Rong, A., Lahdelma, R., 2007. CO2 emissions trading planning in combined heat and power production via multi-period stochastic optimization. European J. Oper. Res. 176 (3), 1874–1895.
Rosenbaum, P.R., Rubin, D.B., 1983. The central role of the propensity score in observational studies for causal effects. Biometrika 70 (1), 41–55.
Rubin, D.B., 2001. Using propensity scores to help design observational studies: application to the tobacco litigation. Health Services Outcomes Res. Methodology 2 (3), 169–188.
Scheelhaase, J.D., Grimme, W.G., 2007. Emissions trading for international aviation—an estimation of the economic impact on selected European airlines. J. Air Transp. Manag. 13 (5), 253–263.
Scheelhaase, J., Grimme, W., Schaefer, M., 2010. The inclusion of aviation into the EU emission trading scheme–Impacts on competition between European and non-European network airlines. Transp. Res. Part D: Transport and Environment 15 (1), 14–25.
Scheelhaase, J., Maertens, S., Grimme, W., Jung, M., 2018. EU ETS versus CORSIA–A critical assessment of two approaches to limit air transport's CO2 emissions by market-based measures. J. Air Transp. Manag. 67, 55–62.
Scotti, D., Volta, N., 2018. Price asymmetries in European airfares. Econom. Transp. 14, 42–52.
Seristö, H., Vepsäläinen, A.P., 1997. Airline cost drivers: cost implications of fleet, routes, and personnel policies. J. Air Transp. Manag. 3 (1), 11–22.
Sheppard, W.W., 1922. Practical Navigation. World Technical Institute.
Stiglitz, J.E., 2019. Addressing climate change through price and non-price interventions. Eur. Econ. Rev. 119, 594–612.
Stock, J.H., Watson, M.W., 2002. Forecasting using principal components from a large number of predictors. J. Amer. Statist. Assoc. 97 (460), 1167–1179.
Tol, R.S., 2007. The impact of a carbon tax on international tourism. Transp. Rese. Part D: Transport and Environment 12 (2), 129–142.
Van Brummelen, G., 2012. Heavenly Mathematics: The Forgotten Art of Spherical Trigonometry. Princeton University Press.
Vasigh, B., Fleming, K., Tacker, T., 2018. Introduction To Air Transport Economics: From Theory To Applications. Routledge.
Verde, S.F., Teixidó, J., Marcantonini, C., Labandeira, X., 2019. Free allocation rules in the EU emissions trading system: what does the empirical literature show? Climate Policy 19 (4), 439–452.
Vespermann, J., Wald, A., 2011. Much Ado about Nothing? An analysis of economic impacts and ecologic effects of the EU-emission trading scheme in the aviation industry. Transp. Res. Part A: Policy and Practice 45 (10), 1066–1076.
Wadud, Z., 2015. Imperfect reversibility of air transport demand: Effects of air fare, fuel prices and price transmission. Transp. Res. Part A: Policy and Practice 72, 16–26.
Wagner, U.J., Muûls, M., Martin, R., Colmer, J., 2014. The causal effects of the European Union Emissions Trading Scheme: evidence from French manufacturing plants. In: Fifth World Congress of Environmental and Resources Economists, Instanbul, Turkey. Citeseer.
Wang, C., Wang, X., 2019. Airport congestion delays and airline networks. Transp. Res. Part E: Logist. Transp. Rev. 122, 328–349.
Wei, W., Hansen, M., 2003. Cost economics of aircraft size. J. Transp. Econ. Policy 37 (2), 279–296.
Wei, W., Hansen, M., 2007. Airlines' competition in aircraft size and service frequency in duopoly markets. Transp. Res. Part E: Logist. Transp. Rev. 43 (4), 409–424.
Xu, Y., 2017. Generalized synthetic control method: Causal inference with interactive fixed effects models. Polit. Anal. 25 (1), 57–76.
Yuen, A.C., Zhang, A., 2011. Unilateral regulation and greenhouse gas emissions: the case of the airline industry. Transp. Res. Part D: Transp. Environ. 16 (7), 540–546.
Zhang, Y., Lin, F., Zhang, A., 2018. Gravity models in air transport research: A survey and an application. In: Handbook of International Trade and Transportation. Edward Elgar Publishing.
Zheng, S., Ge, Y.-E., Fu, X., Jiang, C., 2019. Voluntary carbon offset and airline alliance. Transp. Res. B 123, 110–126.