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Short-haul flights ban in France: Relevant potential but yet modest effects of GHG emissions reduction

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ABSTRACT

The French government has taken a new measure of limiting the exercise of traffic rights to reduce emissions, in particular, the bill to ban short-haul flights where a train alternative of 2:30 h or less exists. Here we quantify the impact of this measure in economic and environmental terms. The results show that although this measure goes in the right direction, it is less effective than expected in reducing greenhouse gas (GHG) emissions from domestic aviation. The adoption of the measure is less ambitious than originally envisaged, and it crucially leaves important domestic air routes out of the ban. As data shows, there is a substitution effect between routes that do not meet the objective of reducing flights and therefore GHG emissions. Moreover, alternative scenarios to the one currently approved have been presented and examined, both in terms of potential extension of routes banned and in substitution effects. Thus, the results show that with this minor modification of the currently approved measure, the substitution effects are removed, and the currently reduced emissions are more than tripled.

1. Introduction

Transport has a very large mitigation potential (Creutzig et al., 2022) and in particular, the air transport is one of the major pollutants sectors worldwide (Van Fan et al., 2018), as it would rank in the top 10 emitters globally if considered as a separate country (ICAO, 2019). Thus, the GHG (especially carbon dioxide, CO_2), in which we also focus particularly) produced by this activity have been extensively studied in the literature (Graver et al., 2018; Loo et al., 2014; Zheng, 2020). These emissions are measured and tracked in detail by different organizations (Mendes and Santos, 2008; OECD, 2022). Contributing >2% of global emissions, aviation is seen as a possible target for mitigation (Delbecq et al., 2022; Dubois and Ceron, 2006; Owen et al., 2010; Planès et al., 2021; Terrenoire et al., 2019), but according to Sky views (2023), the sector is lagging behind in decarbonisation efforts. International aviation and shipping emissions may be regulated by several policies, e.g. domestic emissions trading schemes, or trading schemes established by the relevant international organizations (Haites, 2011), although there might be partial avoidance practices (Cames, 2007).

In the European context, aviation accounted for 3.8% of total CO_2 emissions in the EU in 2017 and is the second-largest source of transport-related GHG emissions after road transport, contributing 13.9% of transport emissions (EUROCONTROL, 2022). Moreover, the European Commission (2020) report and (Lee et al., 2021) show that the combined non- CO_2 climate impacts from aviation activities are at least as important as those of CO_2 alone.

Therefore, the European Union (EU) is acting to address aviation emissions (European Commission, 2021). These initiatives include the adoption of a series of legislative proposals to achieve climate neutrality by 2050, with a target of at least a 55% net reduction in GHG emissions by 2030 (European Comission, 2018). One of these proposals, the review of EU climate legislation, including the European Union Emissions Trading System (EU ETS), has been in place since 2012, requiring all airlines operating in Europe to monitor, report, and verify their emissions and surrender allowances to cover their emissions. This measure has reduced the carbon footprint of the aviation sector by over 17

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million tonnes per year (9% of the total emissions) (European Union, 2017). Other actions to reduce CO_2 emissions in the aviation sector include fuel efficiency improvement (ICAO, 2019) or operational measures, such as modernizing air traffic management technologies and procedures (EUROCONTROL, 2022). In addition, the EU's "Fit for 55" package to reduce GHG emissions includes the ReFuel EU Aviation Regulation (European Comission, 2023). This regulation establishes rules to promote sustainable aviation fuels across the EU, such as the obligation to gradually increase the percentage of sustainable aviation fuels or the need to report the fuel used by both airlines and suppliers (*European Union,* 2023).

In this context, France has recently gone further in the context of other transition measures[1] and adopted a measure limiting the exercise of traffic rights due to serious environmental problems (European Union, 2022). This policy bans the short-distance flight routes when there is the alternative of making the journey by train in <2:30 h (details can be found in (European Union, 2022)). Even if this seems to be a step forward in the objective of reducing the emissions generated by the aviation sector, it has been widely criticised by different environmental groups (Greenpeace, 2022), as it is considered insufficient. Authors like (Dobruszkes et al., 2022) also state that such policies have little effect on emission reductions. It can be argued that this measure is among the pioneering ones (especially on banning) worldwide, and measures of similar nature are being considered in other countries, especially European ones. The final measure turned out to be less ambitious than initially proposed by the Citizens' Climate Convention (CCC, 2020) though, where the time limit was set at 4 h. In this way, setting the limit in 2:30 h have narrowly left out important domestic air routes.

This ban only affects three domestic routes (the connections between the Orly airport in Paris with the cities of Lyon, Bordeaux and Nantes) since the 2:30 h are calculated considering the time to travel from airport to airport. It has been criticised that it does not really have that much impact on these routes since according to the historical data (Eurostat, 2023), the routes between Paris and these three cities have had more flights and passengers from Charles de Gaulle airport than from Orly. In addition, these routes from Orly airport had already been drastically reduced due to the pandemic (Eurostat, 2023). Moreover, there may be a substitution effect between Paris airports and these routes from Charles de Gaulle may increase, reducing the effect of the measure, that will be analysed. Furthermore, only commercial flight routes are included, as private aviation (non-commercial flights) is out of the focus.

With the aim to contributing to the expected impact of this policy, this paper estimates the climate and socio-economic impacts of the policy along supply chains and countries using Input-Output (IO) analysis. The IO models display the interconnections between all the economic activity sectors within an economy (or within several economies). They are particularly useful to calculate the whole overall socio-economic impact, as they consider the whole value chain to produce the service (in this case air transport).

For this purpose, we analyse two alternative scenarios: The first one focused only on the air routes that have been actually banned. This first scenario (scenario 1) will serve to evaluate the policy in this initial phase, as it was done with the EU ETS (European Union, 2004) and also to increase public acceptability of the policy, as in (Maestre-Andrés et al., 2021). A second more ambitious one (scenario 2), also includes some more air routes considering that instead of airport-to-airport trips, city-to-city routes are included. The main reason for this new scenario is to analyse the more plausible situations in which travellers want to arrive at the destination city and not at the destination airport. The IO models also include the substitution effect of transport modes, in this case the increase in activity of rail transport (as is the objective of the measure). Thus, for each of the scenarios, on the one hand the isolated impact of the reduction in air transport will be measured (scenarios 1a and 2a), and on the other hand, the overall impact, including the increase in rail transport (scenarios 1b and 2b).

[1] E.g., launching the Ecological Transition Plan (ETP), see also (Hachaichi and Talandier, 2023) on the estimates of the Ecological Footprint, in conjunction with a spatially-nested approach, as a monitoring framework.

2. Methods

Several studies have explained and highlighted the strengths and weaknesses associated with top-down IO approaches (and bottom-up life cycle assessment approaches) to consumption-based accounting, as in (Hertwich and Peters, 2009; Kokoni and Skea, 2014; Peters, 2010; Sun et al., 2019; Wiedmann, 2010). The IO models are macroeconomic models that represent the interdependencies between different sectors in a quantitative way. The practical applications of IO analysis derive from Leontief's model (Kuznets, 1941; Leontief, 1937, 1936). IO Tables (IOT) allow to empirically represent the complete economic structure of a region or country, as well as the multiple relationships between the sectors that compose it (Simpson and Tsukui, 1965). In fact, together with national accounts, they constitute the central pillar of the economic accounts in any country or region. Essentially, the IOTs record the total production of each sector and the destination of this production. Eq. 1 below shows that the output of a sector is equal to intermediate consumption plus final demand for all sectors in the Leontief model:

$$x_i = z_{i1} + z_{i2} + \dots + z_{ij} + \dots + z_{in} + f_i = \sum_{j=1}^{n} z_{ij} + f_i \tag{1}$$

Where x_i is the output of the i-th sector, z_{ij} are the flows from sector i to sector j and f_i is the total final demand of the i-th sector (private consumption, government expenditure, investment, and exports). In matrix terms:

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nn} \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} + \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} \tag{2}$$

$$\mathbf{x} = \mathbf{Z1} + \mathbf{f} \tag{3}$$

Where **Z** is the inter-industry transactions matrix and **x** and **f** are the output and final demand vectors. If we define the technical coefficients (the direct input requirements for each industry per unit of output) as: $a_{ij} = \frac{z_{ij}}{x_i}$; The model can be formulated as follows:

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} \tag{4}$$

$$\mathbf{x} = \mathbf{Ax} + \mathbf{f} \tag{5}$$

Where **A** is the matrix of technical coefficients. Each coefficient $[a_{ij}]$ in the matrix measures the output of sector *i* from sector *j*. If we clear **x** in the equation, we obtain the basic Leontief model:

$$\mathbf{x} = [\mathbf{I} - \mathbf{A}]^{-1}\mathbf{f} = \mathbf{Lf} \tag{6}$$

Where **L** is the so-called Leontief inverse matrix, technology matrix or production multiplier matrix. The coefficients of this matrix $[l_{ij}]$ indicate the increase in the output of sector *i* that is necessary to satisfy an increase of one additional unit in the final demand of sector *j*. Each element of the main diagonal is always >1 ($l_{ij} > 1$) since it includes the direct effect of the increase in demand on the production of its own sector plus the indirect effects on other sectors.

To measure the impacts on the change in final demand for a sector, it is enough to change the values in the final demand vector ($\bar{\mathbf{f}}$) and multiply it by the inverse Leontief matrix (**L**). In particular, the substitution is exact in economic terms of the final demand (hence the magnitudes of change are properly captured), but it takes the closest economic structures possible in such setup. In particular, the substitution occurs in the final demand of the French households, in the final demand of the French air transport sector. The difference between the new output vector ($\overline{\mathbf{x}}$) and the original output vector ($\mathbf{x}$) will be the total impacts of the change in final demand.

$$\overline{\mathbf{x}} = [\mathbf{I} - \mathbf{A}]^{-1}\overline{\mathbf{f}} = \mathbf{L}\overline{\mathbf{f}} \tag{7}$$

$$\Delta\text{OUTPUT} = \mathbf{x} - \overline{\mathbf{x}} \tag{8}$$

The above simplified framework is considered here in a multiregional IO (MRIO) context (see formulations e.g. in Chenery, 1953; Isard, 1951; Leontief, 1953; Miller and Blair, 2022; Moses, 1955; Tukker and Dietzenbacher, 2013). In this case, the final demand vector consists of values for each of the sectors in each of the countries (sectors and countries can be seen in complementary material). As was discussed, the economic activities that will be directly affected by this policy are the French air and rail transport sectors. Thus, the rest of the sectors remain the same and the final demand of French aviation sector will be decreased in each case depending on the number of passengers affected, resulting in a new final demand value ($\overline{f}_{FRA,TAIR}$). This decrease in terms of output will be obtained from the sum of the price of the flight ticket of all travellers affected by the new measure (the acquisition of this data is explained in the section below). In the same way, the final demand of French rail sector will increase in 1b and 2b cases, resulting also in a new final demand value ($\overline{f}_{FRA,TAIR}$).

$$f_{AUT,PARI} \begin{pmatrix} \vdots \\ \overline{f}_{FRA,TRAI} \\ \vdots \\ \overline{f}_{FRA,TAIR} \\ \vdots \end{pmatrix} f_{WWM,EXTO}$$

This $\mathbf{L}$ matrix can also be used to calculate the output multipliers, which is defined for sector i as the total value of production in all sectors in the economy that is required to satisfy a unit increase in the final demand of sector i. The output multiplier of sector i is calculated as the sum of column i in the matrix $\mathbf{L}$. Moreover, the matrix $\mathbf{L}$ multiplied by the coefficients associated with any indicator will allow the multiplier effect of that indicator to be calculated (Rasmussen, 1956).

Thus, the multiplier effects of indicators such as value added, employment or emissions could be calculated by simply multiplying the $\mathbf{L}$ matrix by the vector of coefficients of the indicator (Cella, 1984; Dietzenbacher, 2005, 2002; Dietzenbacher and Van Der Linden, 1997; Miller and Blair, 2022; Miller and Lahr, 2001; Oosterhaven, 1988). In this way, the GHG emissions are calculated as:

$$\text{GHG} = \mathbf{e}[\mathbf{I} - \mathbf{A}]^{-1}\mathbf{f} = \mathbf{eLf} \tag{9}$$

Where $\mathbf{e}$ is the vector of coefficients of GHG emissions. The emissions with alternative scenarios are calculated as:

$$\overline{\text{GHG}} = \mathbf{e}[\mathbf{I} - \mathbf{A}]^{-1}\overline{\mathbf{f}} = \mathbf{eL}\overline{\mathbf{f}} \tag{10}$$

And the change in total GHG emissions is calculated like[2]:

$$\Delta\text{GHG} = \text{GHG} - \overline{\text{GHG}} = \mathbf{e}(\mathbf{x} - \overline{\mathbf{x}}) \tag{11}$$

In a similar way, the changes in value-added or employment are calculated like:

$$\Delta\text{VA} = \text{VA} - \overline{\text{VA}} = \boldsymbol{\pi}(\mathbf{x} - \overline{\mathbf{x}}) \tag{12}$$

$$\Delta\text{EMP} = \text{EMP} - \overline{\text{EMP}} = \boldsymbol{\mu}(\mathbf{x} - \overline{\mathbf{x}}) \tag{13}$$

Where $\boldsymbol{\pi}$ and $\boldsymbol{\mu}$ are the vectors of coefficients of value-added and employment, respectively.

2.1. Data availability

For the analysis, we have combined data from several sources. To consult the current air routes and the number of flights, the Eurocontrol Network Manager interactive analysis tool (FATHOM)[3] has been used. This tool allows to access the data of all air traffic flying over Europe and provides information on routes, traffic, delays, or fuel consumption. To obtain data on the number of passengers, we have used is the “Air Transport Statistics” by Eurostat. In particular, the “Air passenger transport between the main airports of France and their main partner airports (routes data)”.[4] To avoid the impact of the COVID-19 impacts in the air transportation sector, and due to the limitations of the EXIOBASE database for those years (essentially nowcasted/projected data, elaborated during the years 2019–2021) the data of 2019 has been used. The data for 2020 and beyond is furthermore severely affected by the closure of the sector during the pandemic and thus the impact of this measure is isolated in a business-as-usual context.[5]

To obtain data on train journey times, the SNCF (“*Société nationale des chemins de fer français*” the acronym in French) was consulted.[6] The SNCF is a French state-owned company in charge of the operation of the French railways under a monopoly regime. Average ticket prices for these routes either by plane or by train have been consulted and taken from different official company webs and web comparators, namely Omio, Booking and Kayak (used prices can be consulted in Table 1).

The methodology described in the previous section is applied to France based on the EXIOBASE 3 (3.8.2 version) MRIO tables at basic prices by product.[7] EXIOBASE 3 provides a time series of environmentally extended MRIO tables for 44 countries (28 EU member plus 16 major economies) and five regions of rest of the world. The industrial classification goes up to 163 industries, which is very useful for accurately determining cross-sectoral connections. Moreover, EXIOBASE 3 offers Investment Matrixes describing the total use of capital goods by industries. The environmental extension including different pollutants and air emissions can be used for consumption-based accounting of GHG emissions (Kokoni and Skea, 2014).

In this case, the analysis is focusing only on France and its domestic routes, but as mentioned earlier IO models allow to measure impacts

Table 1
Prices used for cost estimation (average one-way prices).

Routes	Flight ticket price	Train ticket price
Paris-Nantes	196€	60€
Paris-Bordeaux	173€	60€
Paris-Lyon	177€	44€
Lyon-Marseille	202€	50€
Paris-Rennes	295€	55€

[2] As a robustness test to the emission coefficients, the direct emissions were also estimated using a tool designed by the European Environmental Agency (EEA), more details can be found in the appendix.

[3] Available at: https://www.eurocontrol.int/tool/network-manager-interactive-analysis-tool

[4] Available at: https://ec.europa.eu/eurostat/web/transport/data/database

[5] It should be noted that by using 2019 data not conditioned by Covid-19, potential sectoral structural changes or trends of recent years may be left out (e.g. differential business organization related to telework, virtual meetings, etc.). This limitation cannot be corrected until post-Covid (general and especially air transport) structural data is available.

[6] Available at: https://www.sncf.com/fr

[7] Available at: https://zenodo.org/record/5589597#.Y-teZa3MJD8

outside the country. Recall that these models measure the entire value chain and in this way the impacts of the intermediate products imported to produce French air services can be measured. The reference year used is 2019, as is the case of passenger's data.

3. Results

Fig. 1 shows the affected routes in both scenarios. Thus, the routes in the scenario 1 are:

- Orly (Paris) – Bordeaux (493 km)
- Orly (Paris) – Lyon (393 km)
- Orly (Paris) – Nantes (344 km)

The scenario 2 would add the following ones (the original proposal slated to affect eight routes (Eccles, 2022; Sky views, 2023), which required the green light from the European Commission:

- Charles de Gaulle (Paris) – Bordeaux (528 km)
- Charles de Gaulle (Paris) – Lyon (413 km)
- Charles de Gaulle (Paris) – Nantes (372 km)
- Charles de Gaulle (Paris) – Rennes (333 km)
- Lyon – Marseille (255 km)

For both scenarios the isolated impact of the air transportation will be measured firstly, and the rail transport effect will be included later. For this second measurement, it is assumed that all the passengers that can no longer fly due to the ban will travel by train to the same destinations. That is, perfect substitution of passengers. Other assumption could be made (switching to other travelling modes or even deciding not to travel anymore), but as the criterion for the elimination of air routes is that there should be a fast rail line, this assumption has been chosen.

Table 2 will show the economic effects in terms of output, value added and employment for both scenarios, measuring the only flight elimination effect (a) and the flight elimination substituted by trains (b). In the 1a scenario, the global output losses would be 281 million €, 144 million € in terms of value added and 850 jobs are lost worldwide. In the case of the 2a scenario, the output losses would be 905 million €, 466 million € in value added and 2738 jobs. As is obvious, restricting this economic activity has negative economic effects and even if the substitution by train mitigates part of this negative impacts, the total economic impacts would still be negative. For both scenarios between 30 and 40% of the negative economic impacts would be mitigated. Thus, the overall economic effects remain negative because air transport is more expensive than rail transport and generates more economic benefits along the value chain. Comparing both scenarios, the impact in the second scenario would be more than three times greater than in the first scenario, as the number of passengers affected would be the triple.

When talking about affected sectors, in the 2a scenario, the air transport sector accounts for almost 60% of the negative impacts. The rest of the most affected sectors in this scenario can be seen in Table 3. In the 2b scenario, the order of the most affected sectors changes, as the train transportation increase would mitigate some of the negative impacts in the supporting sector. The total difference of both cases would be 314 million €, but the positive effect in the rail transportation sector alone would only be 202 million €. This means that with substitution more that 100 million € of negative effects would be mitigated in auxiliary sectors. When comparing the cases where the substitution by train is made and not, the 21% of negative effects in the (74) NACE sector[8] would be mitigated. The cases of sectors (63) and (65) are especially relevant in this regard, since the 74% and 73% of the negative effects would be mitigated respectively.

Besides France, the most affected countries and regions in output by the ban are shown in Table 4. In the 2a scenario, 80% of the impacts occur in France, but in the 2b scenario, it drops to 76%. These countries can be classified according to the most affected sectors. The western countries would be affected mainly because their air transport and auxiliary sectors would be affected. On the other spectrum, the remaining countries would primarily be affected because the extraction of crude petroleum sector would be affected. China is the exception here, as the most affected sector would be the manufacture of electrical machinery. Comparing both cases, the activity that would drop the most is the extraction of crude petroleum, since the air transportation is much more demanding of this service that the train transportation.

The fall in CO_2 emissions would stand at 155 thousand metric tons for the French aviation sector in the first scenario (0.5% of the emissions of the sector) and 502 thousand metric tons in the second scenario (1.6% of the emissions of the sector), as can be seen in Table 5. When comparing the reduction of emissions to the total emissions of France, the ones reduced in the rest of the value chain of France are also included. Thus, an additional 6 thousand metric tons of CO_2 would be reduced in the rest of France and another 15 additional thousand metric tons in the rest of the world. In the second scenario the CO_2 emissions reductions would be 16 thousand metric tons in the rest of sectors (other than air transport) of France and 49 thousand metric tons in the rest of the world.

In this case, scenario 2 would reduce more than three times the emissions of scenario 1. Comparing the reduction in relative terms of the CO_2 emissions and output, emissions would be reduced >10 times in all cases. Even if the total reduced CO_2 emissions would be lower in the case where the substitution by trains is included, the multiplier is higher that when not, as including rail transport would increase output much more than CO_2 emissions in relative terms. This shows that the rail transport is a good alternative to air transport when the objective is reducing CO_2 emissions.

Nevertheless, the reduction of emissions is a global concern. Table 5 focuses only on the emissions reduced in France (90% of the total reduction, i.e., an additional 10% of CO_2 emissions reduction is found globally, reaching 176, 138, 567 and 453 thousand metric tons of CO_2 emission reduction respectively in the scenarios 1a, 1b, 2a, 2b). In addition, as mentioned in the introduction, the combined non- CO_2 climate impacts of aviation activities are at least as important as CO_2 alone.

Thus, Fig. 2 shows the total emissions reduced of GHG (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Sulphur Hexafluoride (SF_6), Hydrofluorocarbons (HFC) and Perfluorocarbons (PFC) as well as some air pollutants such as Sulphuric Oxides (SOx), Nitric Oxides (NOx), Ammonia (NH_3) and Carbon Monoxide (CO) relative to the output in a global level. Being above the output line means that the relative reduction of that type of emission is bigger than the reduction in output. Note that in this case the multipliers are smaller, as in Table 5 in the 2a scenario the multiplier was 13.6 and globally the multiplier is "only" 3.4. The reason is that globally, due to the direct and indirect purchases of the French aviation sector, still global emissions fall (slightly in percentage terms, in relation to global ones) and output as well (even more slightly) but in a smaller proportion than emissions. In other words, emissions fall 340% more than output.

As can be seen in Fig. 2, the reductions of emissions in CO_2, N_2O, NOx and CO are worth mentioning, more so if only the French context is considered. In these four cases >90% of the reductions would be from France since these substances are very present in the final air transport service. In contrast, for the emissions of the other gases studied the impacts would be much more globally distributed, as these emissions are generated much earlier in the air services value chain. The difference between the two scenarios included in the figure is very relevant, as in all gas emissions the multiplier is higher in the 2b scenario. This means that rail transport is less polluting relative to output for all gases.

[8] Classification in supplemental files (Table 8).

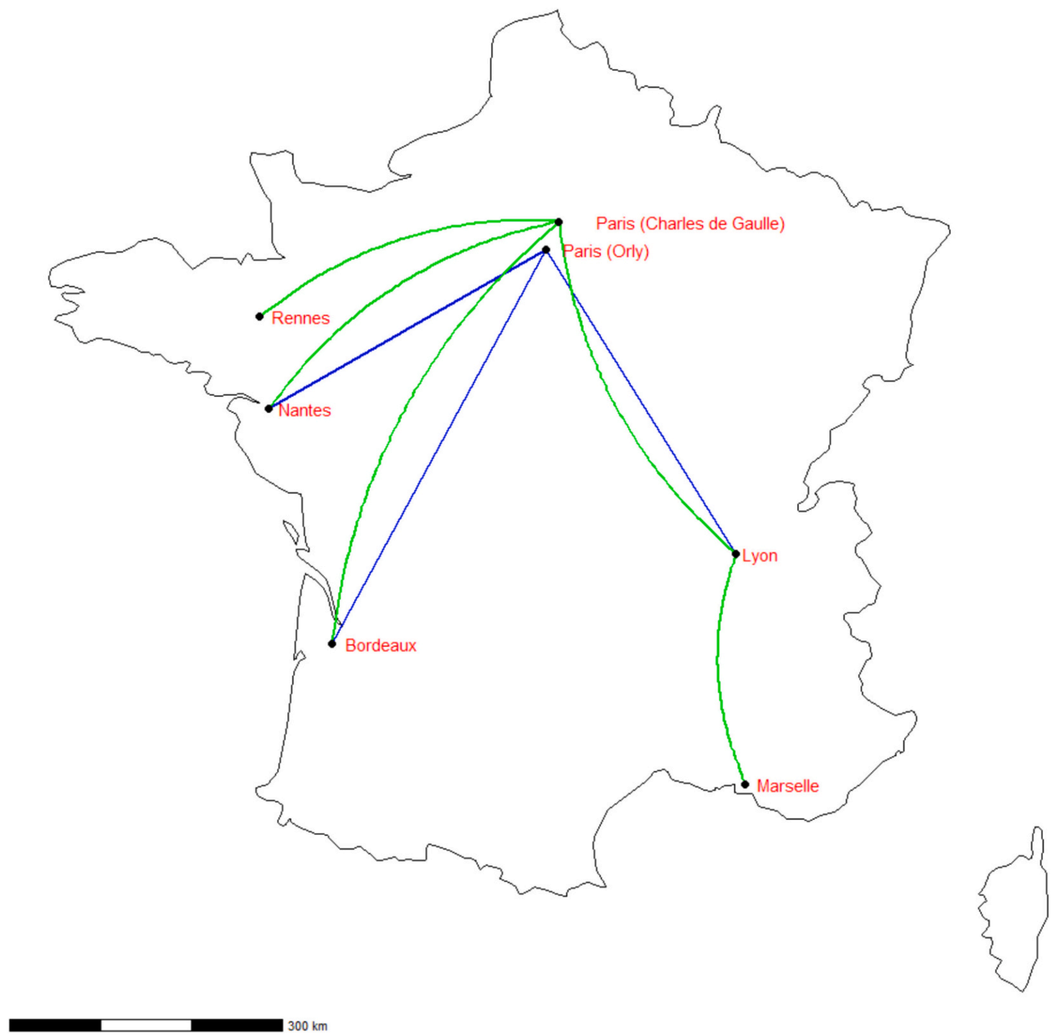

Fig. 1. Affected routes (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).
Note: Points show the airports location. Scenario 1 (actual scenario) routes are shown in blue, Scenario 2 routes are shown in green.
Source: own elaboration.

Table 2
economic effects of both scenarios isolating air transport and including substitution by train (millions of € and number of employees).

	Scenario 1		Scenario 2	
	1a	1b	2a	2b
OUTPUT	−281	−177	−905	−591
VA	−144	−98	−466	−325
Employment	−849	−533	−2738	−1776

3.1. IO limitations and uncertainty discussion

The limitations of the IO analysis and its potential uses have been largely discussed in the literature (Bickel, 1987; Jensen, 1980; Líšková, 2015; Miller and Blair, 2022; Oosterhaven, 2023; Richardson, 1972; Ten-Raa, 2005; West and Jackson, 2004; Wiedmann et al., 2010). When being compared to other methods, or to highlight we usually find those related to the Leontief's basic assumption of constancy of input coefficient of production (even with dynamically modelling, on the drivers of change), constant returns of scale and technique of production, linearity, lack of factor substitution, or of price adjustments mechanisms. Understanding such limitations, but also the contexts and types of studies for which these are more acceptable, together with the strengths of IO, when the analysis is of high use and explanation power, etc., the discussions of limitations then tend to move more into the questions within data and modelling choices, their uncertainties, etc. The evaluation of uncertainties in input-output and related studies has been addressed, among others, by Bessembinder (1995), Bullard (1976), Chen et al. (2018), Jensen (1980), Lenzen (2001), Lenzen et al. (2010), Roy (2004), Temurshoev (2015), Weber (2008), Wiedmann et al. (2008), Wilting (2012), Yamakawa and Peters (2009). Along such literature, it is often showed that they may arise from various sources, namely data reliability, allocation, potential aggregation biases, imports assumption, technological changes, etc. As briefly hinted when explaining the data and modelling choices, even when always uncertainty and potential errors are likely to remain (being difficult to quantify, see e.g. Peters et al., 2007), we aimed for minimizing as much as possible several potential errors, or biases, etc. Especially with the use of multiregional input-output data (to reduce those usually associated with trade assumptions, boundaries/geographical coverage, etc. with respect to e.g. national IO choices), furthermore with a widely chosen and accepted database (especially regarding environmental satellite accounts such as carbon emissions and to avoid aggregation biases due to the very high sectoral disaggregation). Also, by combining this type of top-down information that we considered more reliable with more sectoral specific, bottom-up one, updated, etc., as well as testing sensitivity to choices. The major uncertainty that we consider the work may have is related to

Table 3
most affected sectors in terms of output besides air transportation (NACE classification).

	Scenario 2a		Scenario 2b	
	Sector	%	Sector	%
1	Other business activities (74)	5.4%	Wholesale trade and commission trade, except of motor vehicles and motorcycles (51)	7.3%
2	Supporting and auxiliary transport activities; activities of travel agencies (63)	5.3%	Other business activities (74)	6.6%
3	Wholesale trade and commission trade, except of motor vehicles and motorcycles (51)	5.2%	Petroleum Refinery (19)	4.1%
4	Petroleum Refinery (19)	3.3%	Hotels and restaurants (55)	2.2%
5	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying (06)	1.6%	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying (06)	2.1%
6	Hotels and restaurants (55)	1.6%	Supporting and auxiliary transport activities; activities of travel agencies (63)	2.%
7	Financial intermediation, except insurance and pension funding (65)	1.3%	Manufacture of electrical machinery and apparatus n.e.c. (31)	1.9%
8	Manufacture of electrical machinery and apparatus n.e.c. (31)	1.3%	Renting of machinery and equipment without operator and of personal and household goods (71)	1.3%
9	Real estate activities (70)	1.2%	Post and telecommunications (64)	1.3%
10	Post and telecommunications (64)	1.1%	Real estate activities (70)	1.3%

Classification is available in supplemental files (Table 8)

the most recent structural changes due to lack of updated data.

The Supplementary Material includes additional estimates and discussions on the robustness and sensitivity of results. As anticipated in note 2, as a robustness test to the emission coefficients, the direct emissions were also estimated using a tool designed by the European Environmental Agency (EEA), which is a bottom-up approach used in the literature on the aviation sector emissions estimates, e.g. in Avogadro et al. (2021). Furthermore, we have also extended the sensitivity analysis to further understand the sensitivity to the year of analysis choice, as in general to further understand and discuss the robustness of the analysis.

3.2. Recent evidence on actual routes and flights

The scenarios we are talking about would be fulfilled if these flights are reduced on the one hand and if they are replaced by the train on the other hand. Since these routes were cancelled on 23 May 2023, the first trends in the adaptation of French transport to this measure can be observed today.

On the one hand, French rail transport broke all-time passenger records this summer (Le Monde, 2023a), increasing by 20% compared to the previous year. In addition, the routes from Paris to Lyon, Bordeaux and Nantes are ranked 1st, 3rd and 4th in the most frequented rail lines respectively.

On the other hand, the air routes between the Charles de Gaulle and

Table 5
CO_2 emissions change relative to their totals in France.

	Scenario 1		Scenario 2	
	a) Only flight	b) Substitution by trains	a) Only flight	b) Substitution by trains
CO_2 France aviation	−0.5%		−1.6%	
CO_2 France	−0.07%	−0.05%	−0.22%	−0.18%
Output France	−0.005%	−0.003%	−0.016%	−0.010%
ΔMultiplier (ΔCO_2/ΔOutput)	(X)13.6	(X)17.8	(X)13.6	(X)17.4

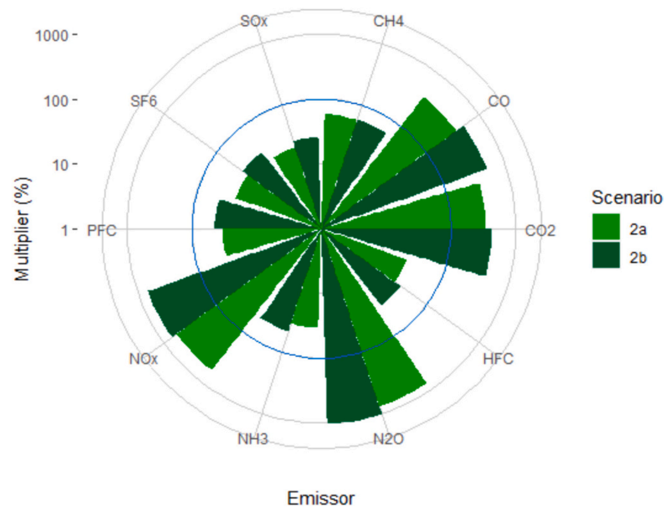

Fig. 2. GHG emissions change to output when only air transport is included and when substitution by train is included.

Table 4
Most affected countries and regions in terms of output.

	Scenario 2a			Scenario 2b		
	Countries	%	Cumulative (%)	Countries	%	Cumulative (%)
1	France	80.3%	80.3%	France	76.6%	76.6%
2	United States	1.7%	82.0%	United States	2.2%	78.8%
3	Germany	1.7%	83.7%	RoW Africa	2.1%	80.9%
4	RoW Africa	1.6%	85.3%	Germany	2.0%	82.8%
5	RoW Asia and Pacific	1.4%	86.7%	RoW Asia and Pacific	1.8%	84.6%
6	Belgium	1.3%	88.0%	China	1.7%	86.3%
7	RoW Middle East	1.2%	89.2%	RoW Middle East	1.6%	87.9%
8	China	1.2%	90.4%	United Kingdom	1.3%	89.2%
9	United Kingdom	1.1%	91.5%	Spain	1.2%	90.5%
10	Spain	1.0%	92.5%	Belgium	1.0%	91.5%
11	The Netherlands	0.8%	93.4%	The Netherlands	1.0%	92.5%

Row: Rest of the World

Lyon Saint-Exupery and Bordeaux-Merignac airports were in all-time highs for this summer, with an increase of 16% and 23% relative to July 2019 respectively (Eurostat, 2023). These figures are even more significant if it is considered that total French air traffic in 2023 is still 9% lower than in 2019 and 10% lower in summer months (EUROCONTROL, 2023). The only route that counterpoises this general trend is that between Charles de Gaulle and Nantes Atlantique airports, where the number of flights in 2023 is 8% lower than in July 2019. Moreover, according to Le Monde (2023b), the three affected routes have been already taken out by Air France at the government's request in 2020, the main airline in France (exceeding 80% of flights for all three air routes).

However, this request by the French government was probably made to give Air France time to adapt to this measure, and then although Air France no longer used these routes, other airlines did, and this ban puts an end to these routes.

With these data, it can be seen that although some passengers have indeed changed their mode of transport to rail, it cannot be concluded that scenario 1b is the most realistic. The real current scenario is probably a sort of 1c scenario with less CO_2 reductions and losses for the air transport sector than 1b, in which the real behavioural change is less stylized given the current law and incentives. The reduction of the three affected routes is substituted by both rail transportation and flights from/to Charles de Gaulle. In this way, on the air routes between Charles de Gaulle and Lyon Saint-Exupery and Bordeaux-Merignac, there are currently 29% and 34% more flights respectively than there would have been if the Orly passenger's substitution had been entirely made by train. Taking together this fact with the aforementioned on the decreasing trend in GHG emission coefficients, notably in air transport, this means that the different estimations made in emissions reduction are overestimated, since part of the flights are replaced and not cancelled, and that the policy is probably even more ineffective in reducing emissions than predicted. Thus, the reduction in CO_2 emissions would be 29% less than estimated in the 1b scenario, keeping them at 98 thousand metric tons.

4. Conclusions and future research

The measure of limiting the exercise of traffic rights due to serious ecological problems has been presented especially by French ministers and President Emmanuel Macron as a policy to cut carbon emissions, claiming to be at the forefront of ambitious climate change policy. The measure is relatively pioneer (other cases exist, truly often more partial and not driven by a whole country, for shortest distances, or introducing taxes instead of bans as in Austria, (WELT, 2020)). There is also a broad scientific consensus worldwide that emission reductions should be a priority objective (e.g. IPCC, 2023) and this measure goes in that direction addressing measures for a sector as transport that presents relevant potential for emission reduction. This paper aims to contribute to the analysis of the policy impacts in environmental and socioeconomic terms.

However, the results are showing that the implementation is still having a quite limited quantitative effect. As discussed, the ambition and arbitrariness of setting the limit at 2:30 h are also criticised by several groups (Greenpeace, 2022), as this means that the mentioned routes from Charles de Gaulle (with the consequent substitution effect) or the route to Marseille are narrowly left out. Furthermore, estimates such as (Le Monde, 2023b) do not consider the airport substitution effect that is taking place. In addition, the same article estimated that the number of flights affected if the CCC proposal (4 h limit) was adopted would be 7 times higher than at present (scenario 1). A stringent ban in this line should take into account other considerations (business-work-family reconciliation, potential limited direct daily service (OECD, 2022), connections, and similar arguments or excuses discussed both by the European Commission[9] and France) but certainly similarly to what is shown here, the GHG emissions reductions would clearly exceed in relative change other economic effects.

This paper therefore aims to quantify the approved scenario together with the scenario in which 2:30 h is maintained as the time limit but is measured on a city-by-city basis. In addition, this scenario would avoid the current substitution effect of Parisian airports and effectively reduce the number of flights. The results show that with only this change in the measure, reduced emissions of CO_2 can be multiplied by >3 times. Apart from CO_2, the reductions of emissions in N_2O, NOx and CO are very relevant.

This ban obviously has negative economic effects on the airline industry, which has to be restructured, and on its entire value chain. Even so, by including rail as a travel alternative, a large part of the negative effects in the value chain are mitigated and that emission reductions are maintained. For the negative economic effects, potential compensations, subsidies, or other type of support could be studied. Moreover, for all gas emissions studied, substitution by train has positive effects, as the rail transport is a good alternative when the objective is reducing emissions. This substitution by rail is also very feasible in a country with such an extensive and high-capacity rail network as France, thanks in large part to the high-speed train. Even more, as highlighted in (OECD, 2022), improvements to rail services should see further routes banned. High-speed rail alongside improved rail networks can make ground travel more attractive and competitive with air travel (as well as remove road traffic to further reduce emissions, see (Avogadro et al., 2021).

As future research, studying the impact of the setting the time limit as proposed by the CCC can be very useful to analyse de trade-off between travel comfort and environmental commitment. Quantifying the impact of the ban in private aviation would be also interesting to search for future improvement. Moreover, studying the impacts of similar measures in other European level, both individually and as European Union, can be useful to legislators in the expansion of such measures. It could be relevant to study the effects of a similar measure for other European countries using this methodology. Not only at the individual country level (e.g. in the surrounding area it could make sense for relatively large countries in the European context: Germany,[10] Spain…) but also for the European Union as a whole, or at least for groups of countries, as e.g. is being proposed by the Netherlands (150 km, with Belgium, etc.). Other contexts, such as the ones of the United States or China, are quite

[9] As summarized in (European Union, 2004), the EU executive said France was justified to introduce the measure provided it is "non-discriminatory, does not distort competition between air carriers, is not more restrictive than necessary to relieve the problem." (…) "Three more routes could be added — between Paris Charles de Gaulle and Lyon and Rennes, and between Lyon and Marseille — if rail services improve." "Those routes currently don't meet the threshold because travellers trying to get to airports in Paris and Lyon don't have a rail connection that would get them in early enough in the morning or late enough in the evening". "Two other proposed routes — from Paris Charles de Gaulle to Bordeaux and Nantes — were excluded from the measure because the rail journey time falls above the two-and-a-half-hour limit".

[10] See e.g. (Reiter et al., 2022) aimed to quantify the potential impact on CO_2 emissions of substituting short-haul flights with rail frequencies in German air travel corridors., discussing as well the assessment in relation to travel time losses.

different in terms of flight distances and land transport alternatives. In any case, e.g. the fact that the US ranks first for emissions from domestic flights (OECD, 2022; Owen et al., 2010) or the hinted advances in China in high-speed rail (Lawrence et al., 2019) indicate that relevant domestic flight reduction potential exists also for such large countries and economies. All in all, the literature is quite consistent (Delbecq et al., 2022; Dubois and Ceron, 2006; European Commission, 2021; Owen et al., 2010; Planès et al., 2021; Terrenoire et al., 2019) in signalling the need of emission mitigation for the aviation sector, emissions reductions, etc. for sustainable climate trajectories.

CRediT authorship contribution statement

Andoni Txapartegi: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ignacio Cazcarro:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ibon Galarraga:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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