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ORIGINAL ARTICLE

The economic and environmental impact of limiting air routes where there is a rail alternative: a case study of Spain

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Abstract
The current Spanish government pact includes a measure aimed at restricting domestic flights on routes where a rail alternative is available with a duration of less than 2.5 h. This measure aligns with similar initiatives undertaken by neighbouring countries, with the French model serving as a prominent example. In this study, we quantify the economic and environmental impacts of this policy using input–output analysis, taking into account the current post-COVID trends in the Spanish air and rail sectors. Given the lack of specific implementation details within the measure, we have developed several scenarios to explore its potential application both presently and in the future. The results indicate that while such measures negatively affect the aviation value chain, these adverse impacts are largely mitigated by the substitution with rail transport. Trains emerge as a superior alternative for reducing emissions, given their relatively low environmental impact. The various scenarios demonstrate significant differences in outcomes, underscoring the importance of the chosen implementation strategy in determining the overall impact of the measure.

Keywords Aviation · Short-haul flights ban · GHG emissions · Economic effects · Spain · Government pact

Introduction

The reduction of greenhouse gas emissions stands as a top priority for the European Union and its member countries. Indicator-based assessments of past and projected climate change, as well as its impacts on ecosystems and society, have been examined at both global and European scales (Metzger and Schröter 2006, EEA-European Environment Agency 2017; Bednar-Friedl et al. 2022), also exploring the sensitivity to changes in climate and socio-economic drivers (e.g. Fronzek et al. (2019)). The European Council's 2014 Conclusions set emission reduction targets, with the approval of the 2021–2030 Framework for Energy and Climate Change Policies (2030 Framework, MTMS 2021). In 2020, the European Council with a set of policy initiatives included in the European Green Deal endorsed a binding EU target, with the ultimate goal of achieving climate neutrality by 2050 and aiming for a 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels, along with at least 32% of energy consumption from renewable sources and a 32.5% improvement in energy efficiency (European Commission 2020a, b; BOE 2021).

The transportation sector remains a significant contributor to greenhouse gas emissions in Europe, accounting for over 27% of total carbon dioxide (CO_2) emissions, with road transport being the primary source of pollution (Marrero et al. 2021). Thus, to achieve climate neutrality by mid-century, transport emissions will have to be reduced by 90% compared to 1990 (European Commission 2020a, b). Studies indicate varying emission reduction potentials for different European countries, ranging from 10 to 30% for industry and

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30 to 80% for road transport (Mertens et al. 2021). Despite a 12.7% emissions decrease observed in 2020 due to reduced transport activity during the pandemic, a return to previous emission levels is anticipated post-pandemic, highlighting the need for sustained efforts (Mertens et al. 2021). In addition, technological advances, increased uptake of alternative vehicles and the shift to renewable fuels have contributed to a decrease in emissions from the transport sector in the last decade (Rottoli et al. 2021; EEA 2023).

Aviation, one of the fastest-growing sources of greenhouse gas emissions, has come under scrutiny in European emission reduction legislation (European Commission 2021). Aviation emissions in Europe have been a significant concern due to their rapid growth and impact on the environment. Despite a 22.5% reduction in total greenhouse gas emissions in Europe between 1990 and 2018, aviation emissions surged significantly during this period (European Commission 2020a, b). For instance, emissions from aviation in the EU28 area rose by 118% compared to 1990 levels, posing challenges to the aeronautical industry and EU itself (European Commission 2021; Montlaur et al. 2021; Marouf et al. 2023).

Notably, the incorporation of the aviation industry into the Greenhouse Gas Emissions Trading System (EU-ETS) aimed to address these emissions, covering all flights within the EU (Mu and Tao 2023). Moreover, the *Updated analysis of the non-CO_2 effects of aviation* report (European Commission 2020a, b) shows that the combined non-CO_2 climate impacts from aviation activities are at least as important as those of CO_2 alone.

In the case of Spain, studies have highlighted the importance of addressing aviation emissions. Research has shown that aviation emissions have been a significant contributor to the country's total emissions, with the electricity sector also playing a substantial role (Cruz-Pérez et al. 2021). Efforts to mitigate aviation emissions in Spain have included exploring alternative fuels and biofuels (Gegg et al. 2014; Filimonau et al. 2018).

In this context, the government pact between the PSOE and Sumar parties for the current legislature includes a specific measure for aviation. This pact, presented on 24 October 2023, includes in Section "Discussion and conclusions" "Guaranteeing the right to housing and quality transport for all" that, as other neighbouring countries have done, the reduction of domestic flights on those routes where there is a rail alternative with a duration of less than 2.5 h will be promoted (PSOE y Sumar 2023). There were political reactions and statements, one of the few with numerical figures on potential emission reductions being the one provided by the Official College of Aeronautical Engineers of Spain (COIAE 2023).

As mentioned in the government pact document itself, this is not a new measure, as it is being discussed and studied in different European countries (Ajuntament de Barcelona 2021; Dobruszkes and Ibrahim 2021; EUROCONTROL 2021; Avogadro et al. 2021; Dobruszkes et al. 2022; Ecologistas en acción 2023; Cantos-Sánchez et al. 2023; Avogadro and Redondi 2024). Studies like Reiter et al. (2022) show the potential of such measures in Germany and Baumeister (2019) and Baumeister and Leung (2021) for Finland also highlighting that trains seem to be the most suitable transportation mode to replace aircraft on short-haul routes. In Austria, it has been decided to impose special taxes on such flights instead of banning them (WELT 2020). Moreover, outside the EU—such as in Australia, Turkey, China and the US—several high-level studies on air-rail substitution have also been conducted (Robertson 2013; Dalkic et al. 2017; Wang et al. 2019 or UBS 2020).

France stands out for implementing a policy imposing restrictions on short-distance flights where a train journey of less than 2:30 h is available, reflecting a shift towards sustainable transportation (European Union 2022; Txapartegi et al. 2024). However, controversies have arisen regarding the measure's ambition, with initial proposals by the Citizens' Climate Convention (2020) suggesting a 4-h limit.

As a result, the government has opted to permanently halt three aviation routes previously operated by the Air France group. These routes include Paris Orly to Nantes, Paris Orly to Bordeaux and Paris Orly to Lyon. The decision to suspend these air links was driven by the availability of a high-speed rail alternative that met specific criteria, including:

- Direct rail connections between the same city pairs served by the airports.
- Seamless travel without the need for train changes, ensuring continuity in the journey.
- Multiple departure and arrival times throughout the day, providing flexibility for travellers.
- The ability for passengers to spend more than 8 h at their destination within the same day.

On the other hand, other shorter routes than Paris Orly-Bordeaux (498 km), such as Lyon-Paris CDG (400 km), Rennes-Paris CDG (328 km) or Lyon-Marseille (277 km), are not suspended because they do not meet all these specific criteria.

The reason for banning this type of flight is that although covering relatively small distances, they can still contribute significantly to greenhouse gas emissions due to the high fuel consumption per passenger mile. Studies like Baumeister and Leung (2021) or Reiter et al. (2022) have shown that short-haul flights can generate twice as many emissions per kilometre or seat-kilometre than long-haul flights. It should also be mentioned that although these routes are the most energy intensive, they account for a small share of total aviation emissions (In the French case, the current ban affects only to the 0.23% of total aviation emissions in France (Le Monde 2023)). In this regard, high-speed trains have garnered attention for their potential environmental benefits, particularly in reducing carbon emissions (EUROPE'S RAIL 2023). Research by Zhang and Nie (2021) in China demonstrated that the introduction of high-speed rail significantly decreased local carbon emissions. Similarly, a study by D'Alfonso et al. (2016) highlighted that the energy consumption of high-speed rail which is electric is much lower than diesel trains due to the higher technical efficiency of electric trains. Moreover, the different operating conditions (fewer stops, i.e. less energy used for acceleration) make the high-speed rail even more efficient.

This measure is very much in line with the current investment in the national high-speed train line, both in increasing the number of routes and in improving the efficiency of the trains (RENFE 2024). The development of the high-speed train has been one of the government's main axes and will continue to be so as stated in the Mobility Plan 2030, in line with the EU Commission's Trans-European Transport Network (TEN-T) project (European Commission 2019; ADIF 2021; MTMS 2021). Moreover, the current Spanish high-speed network has proven to be particularly efficient (MTMS 2023; ADIF 2024a).

This paper seeks to enhance our understanding of the anticipated effects of the proposed policy by estimating its climate and socio-economic impacts across supply chains and countries, employing input–output (IO) analysis. IO models serve as comprehensive frameworks illustrating the interdependencies among all economic activity sectors within a single economy or across multiple economies. Their utility lies in their ability to assess the holistic socio-economic impact, as they account for the entire value chain involved in producing a service, such as air transport in this context. IO models have been used to measure economic and environmental impacts of different transport-related research (Oosterhaven and Stelder 2002; Yu et al. 2021; Keček et al. 2022; Abbood and Meszaros 2023). Through IO analysis, this study aims to provide a nuanced evaluation of the policy's ramifications, shedding light on its implications for both the climate and various socio-economic factors.

Given the lack of specific details within the government agreement, this study will explore various future scenarios regarding the implementation of the proposed measure. These scenarios will be developed to facilitate comparative analysis, allowing for an examination of potential outcomes under different conditions. By delineating multiple scenarios, this study aims to offer a comprehensive exploration of the implications associated with the policy, thereby aiding in informed decision-making and policy formulation.

The first scenario will exclusively analyze the prohibition of flights on routes with a rail alternative of less than 2:30 h, as the original text of the proposed ban states. It is worth mentioning that this time will be measured from city to city and not in travel time at the airport, as in the French case. Considering travel time from airports has created a paradox where flights to the same city, such as Lyon, may or may not fall under the policy depending on the Parisian airport of departure (Charles de Gaulle or Orly), even though the train alternative from Paris' Gare du Nord station remains the same. Although the connection to Barajas airport is under construction and is expected to be available by 2026 (RENFE 2024), there are currently no high-speed rail connections to airports. However, several important routes are left out of this measure by a few minutes (Madrid-Valencia, Madrid-Sevilla or Barcelona-Valencia). Thus, a second scenario is calculated where a limit of 4 h is set. The reason for setting this limit at 4 h is that this was the original proposal in the French case (the only country that has implemented it as a full national policy), although it was eventually reduced (Convention Citoyenne pour le Climat 2020). The aim of this second scenario is to quantify a more ambitious alternative of the measure in order to compare it with the first scenario. Finally, the third scenario will project a future scenario wherein the high-speed rail lines, presently under construction, become operational. This scenario is designed to assess the aggregated impact of the proposed policy in conjunction with the realization of high-speed rail infrastructure objectives in Spain.

The IO models encompass the substitution effect of transport modes, particularly relevant in this context given the intended increase in rail transport activity as a result of the policy measure. Therefore, each scenario will be analyzed to gauge both the isolated impact of the reduction in air transport and the overall impact, accounting for the concurrent increase in rail transport. This dual assessment approach allows for a comprehensive understanding of the policy's implications, considering not only the direct effects on air transport but also the broader dynamics within the transportation sector resulting from mode substitution.

The "Methodology" section details the methodology and data used. The "Definition of scenarios and ranges" section describes the different scenarios and ranges considered for complementary analyses, being quantified in the "Results" section of results. Finally, the "Discussion and conclusions" section focuses on the conclusions of the research and policy implications.

Methodology

This study employs input–output (IO) models to analyze the economic and environmental impacts of the discussed measure (more methodological details can be found in appendix 1). IO models, grounded in the work of Leontief, provide a framework for understanding interdependencies between economic sectors. The analysis uses input–output tables (IOTs) to quantify sectoral outputs and their distribution, serving as a basis for assessing the broader economic effects of policy changes.

The central tool is the Leontief inverse matrix, which captures the ripple effects of changes in final demand across the economy. Policy impacts are simulated by adjusting the final demand vector for the Spanish aviation and rail sectors based on the affected passenger volumes and ticket prices. The model also calculates multiplier effects (see Cella 1984; Oosterhaven 1988; Dietzenbacher and Van Der Linden 1997; Miller and Lahr 2001; Dietzenbacher 2002, 2005; Miller and Blair 2022, Oosterhaven, 2024) for indicators such as greenhouse gas emissions, value added and employment, enabling a comprehensive understanding of economic and environmental consequences.

Data availability

For the analysis, we have combined data from various sources. The commercial air routes, with their respective numbers of flights and passengers in 2023, have been obtained from AENA (2023), the Spanish public company which manages the airports. Train journey times were consulted in ADIF (2024b), the public company under the Ministry of Transport and Sustainable Mobility that manages the operation of Spain's railway lines.

The average air fares for the selected routes in 2023 have been calculated by obtaining monthly averages from different company websites (e.g. Iberia, Vueling, Air Europa) and web comparators (mainly Omio, Booking and Kayaks). These comparators provide estimates of the average price of a route, which was obtained along 2023 for each month. These monthly averages have been cross-checked with AENA's monthly passenger data to obtain the annual average. Additionally, as air transport is a service with high seasonality, the monthly evolution of the national air transport Consumer Price Index (CPI) of the Spanish National Statistical Institute (NSI 2024a, b) has been cross-checked, being used this last one to create a confidence interval, as well as with the main statistics provided by Andrés Martínez et al. (2017); details of the process can be found in appendix 2. Rail ticket prices by quarter in 2023 for the same routes have been consulted in CNMC (2023–2024). In this case, these data have been crossed with the number of rail passengers per quarter to obtain the average annual price. Conversions between purchaser and basic prices were performed following Cazcarro et al. (2022). The annual averages can be consulted in the appendix 2 (Table A1).

The methodology described in the previous section is applied to Spain based on the EXIOBASE 3 (3.8.2 version) multi-regional input–output (MRIO) tables at basic prices by product (Standler et al. 2021). 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 the 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 can be used for consumption-based accounting of greenhouse gas (GHG) emissions (Kokoni and Skea 2014). Recall that these models measure the entire value chain and in this way the impacts of the intermediate products imported to produce Spanish air services can be measured. The reference year used is 2019, to avoid the impacts related to the COVID-19. In addition, to enhance the robustness of the analysis, direct emissions were also estimated using a tool developed by the European Environment Agency (EEA) (appendix 3).

However, as shown in the section on the current state of short flights in Spain, the sector has undergone a substantial improvement in environmental efficiency, both in terms of the aircraft used and the increase in the number of passengers per flight (it has been found that carbon emissions of individual flights differ tremendously, see Baumeister, 2017). In order to reflect this new reality of the sector, the emissions coefficients of the original EXIOBASE matrix have been modified. Specifically, the CO_2, CH_4, N_2O, SOx, NOx, NH_3 and CO emissions coefficients for the aviation sector have been modified using the 2023 data obtained from AENA (2023) and NSI (2024c). The rest of the sectors have been updated using data from OTEA (2024), which provides updated annual emissions estimates up to 2023 for the major sectors of the Spanish economy.

Definition of scenarios and ranges

Main scenarios

As can be observed, the first scenario only includes three air routes, highlighting the Madrid-Barcelona route, the connection between the two main Spanish cities. The second scenario adds a further 11 air routes that would be abolished if the measure were to set the rail alternative limit at 4 h. The third scenario extends the suppressible air routes by a further 8 routes. The case of Madrid-Jerez de la Frontera deserves a special mention, as it is a journey that can actually be made by train in less than 4 h but not directly (a stopover in Seville is necessary). For this reason, it has been decided to include it in the third scenario (Table 1).

The subsequent two sections will undertake an analysis of the present status of air and rail traffic along routes presently accessible via rail within a 4-h timeframe (scenarios 1 and

Table 1 Affected air routes for each scenario with their corresponding train time alternative

Routes		Train times
First scenario: 2:30 h limit		
1	Madrid-Valencia / Valencia-Madrid	1:49
2	Alicante-Madrid / Madrid-Alicante	2:17
3	Barcelona-Madrid / Madrid-Barcelona	2:29
Second scenario: 4:00 h limit		
4	Barcelona-Valencia/ Valencia-Barcelona	2:52
5	Madrid-Málaga / Málaga-Madrid	2:47
6	Madrid-Pamplona / Pamplona-Madrid	2:59
7	Madrid-Santiago de Compostela / Santiago de Compostela-Madrid	3:16
8	Madrid-Sevilla / Sevilla-Madrid	2:42
9	La Coruña-Madrid / Madrid-La Coruña	3:48
10	Granada-Madrid / Madrid Granada	3:31
11	Logroño-Madrid / Madrid-Logroño	3:16
12	Madrid-Asturias	3:11
13	Madrid-Castellón	2:59
14	Madrid-Murcia	2:45
Third scenario: 4:00 h limit (including feasible routes in the future)		
15	Madrid-Jerez de la Frontera / Jerez de la Frontera-Madrid*	3:47*
16	Madrid-Badajoz / Badajoz-Madrid	-
17	Madrid-Bilbao / Bilbao-Madrid	-
18	Madrid-San Sebastián / San Sebastián-Madrid	-
19	Madrid-Santander / Santander-Madrid	-
20	Barcelona-Alicante / Alicante-Barcelona	-
21	Barcelona-Bilbao / Bilbao-Barcelona	-
22	Barcelona-San Sebastián / San Sebastián-Barcelona	-

2). This analysis aims to acquire an in-depth comprehension of the prevailing trends observable on these specific routes.

Current status of short-haul flights in Spain

COVID-19 had a devastating effect on aviation worldwide and Spain was no exception. However, 2023 has already surpassed the 2019 data (last pre-pandemic year), with an 8.31% increase in the number of passengers on international flights and a 2.09% increase in the number of domestic flights (AENA 2023). However, several significant changes have been observed in this transitional period, changing the outlook for the Spanish airline industry.

On the one hand, there have been significant changes in the aircraft models used for domestic flights. The most widely used aircraft type, the Aerospatiale ATR-72, has gone from operating 18.37% of flights in 2019 to 27.20% in 2023 (AENA 2023). Considering that this aircraft model emits, on average, less than half the CO_2 emissions per flight of the next two most used models (BOEING 737–800 and AIRBUS A320), this change is very significant in terms of reducing emissions (ATR 2023).

On the other hand, particularly the air routes identified by this directive as being eligible for cancellation have also undergone significant changes. As can be seen in the AENA data (appendix 1), both the number of passengers and the number of commercial flights have decreased significantly.

Current state of high-speed trains prices in Spain

The Spanish high-speed rail sector has undergone significant transformations since the pre-pandemic era, driven largely by the European Union's Fourth Railway Package, which initiated the liberalization of passenger rail services in December 2020. This development ended RENFE's monopoly and introduced competition from companies like OUIGO and Iryo, resulting in increased supply and lower ticket prices for passengers. RENFE responded by launching its low-cost brand, AVLO, to compete on price. These changes have driven remarkable growth, with passenger volume reaching record levels in 2023 and traffic growth exceeding 40%, marking a recovery that surpasses pre-pandemic levels. A second phase of market liberalization is anticipated, focusing on expanding access to additional regions such as Murcia and Galicia.

The liberalization has profoundly impacted pricing dynamics, with routes serviced by multiple operators seeing ticket prices drop by an average of 23% compared to 2022 and by 65% compared to pre-pandemic levels. This trend aligns with infrastructure enhancements led by ADIF, the public entity managing railway infrastructure, which aims to ensure that 90% of citizens live within 30 km of a high-speed station. Major ongoing projects include connecting Extremadura to the central network, extending services to Murcia and Santander, developing the Basque Y network and enhancing connectivity to Madrid's Barajas airport. While progress is steady, some projects face long timelines, and environmental and economic considerations remain critical due to the high costs and environmental impacts of construction.

Spain's cost-efficient high-speed rail infrastructure, averaging €17.7 million per kilometre compared to €45.5 million in other countries, highlights the sector's competitive edge (MTMS 2023; INECO 2023, see also for additional estimates, OTLE (2024)). However, environmental concerns during construction, such as greenhouse gas emissions and material use, require careful evaluation in Spain (see Bueno et al. (2017); Kortazar et al. (2021); Damián and Zamorano (2023)). Future developments prioritize integrating existing networks with airports and completing advanced projects to minimize ecological and financial burdens. These efforts reflect a balance between expanding access and mitigating environmental impact, ensuring the sustainable growth of Spain's high-speed rail network.

Affected routes and summary of scenarios implemented accordingly

As it was mentioned, after defining the three scenarios, the isolated impact of air transportation cessation is initially assessed (scenarios A), subsequently augmented by the integration of potential passenger substitution onto rail modalities (scenarios B). In examining the substitution of rail travel, it is essential to consider the diverse dynamics underlying changes in passenger behaviour (Fig. 1).

The potential decline in total passenger numbers due to restrictions on air travel highlights the complexity of transport mode substitution. In France, the only country to implement such measures, the report by the Ministère de la Transition Écologique (2023) indicated that 63% of passengers stopping using air travel would opt for trains, 30% cars and 7% might choose not to travel (see also on the effects, Txapartegi et al. (2024) and appendix 5 here). In Spain, where alternative air routes are unavailable for affected connections, rail substitution is more feasible, but passenger behaviour remains uncertain. The banning of these air routes would presumably be accompanied by an increase in high-speed train service to accommodate these passengers (see, e.g., Givoni and Dobruszkes (2013); Pagliara et al. (2013);

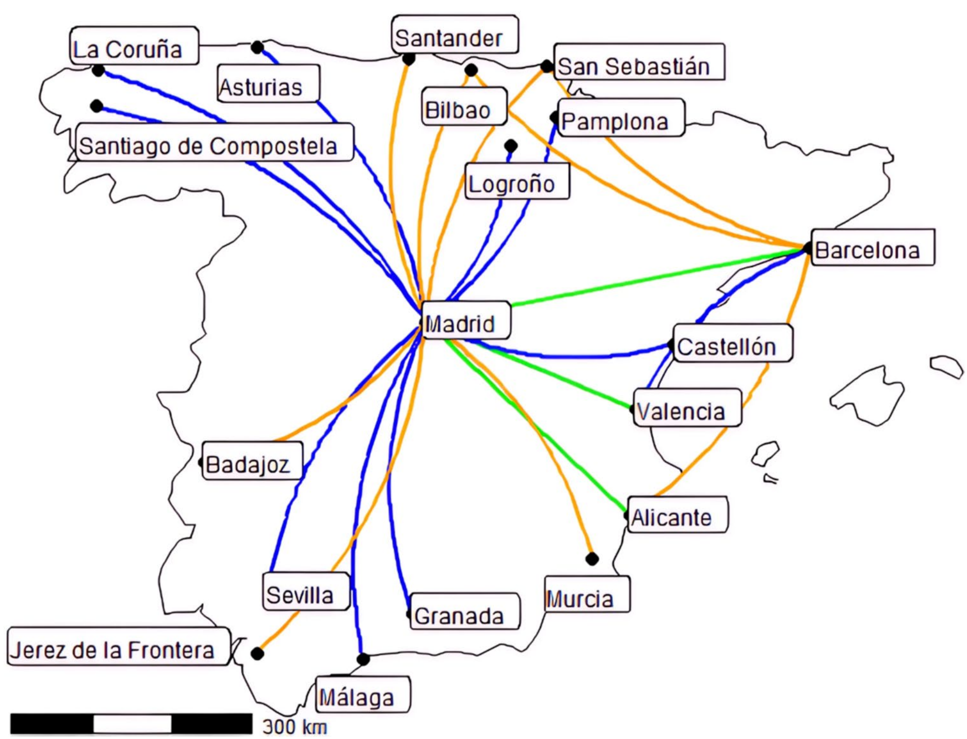

Fig. 1 Affected routes of each scenario. The green routes correspond to the first scenario, the blue ones to the second scenario and the orange ones to the third scenario

Zhang et al. (2019); Avogadro and Redondi (2023); (Meixell and Norbis, 2008; DT, 2014; Álvarez-Antelo et al., 2025), and even generate induced effects (up to an additional 10–20% due to improved services according to Givoni and Dobruszkes (2013)). Additionally, this shift could reduce car usage and non-travel rates.

Dynamic factors such as demand evolution and price sensitivity further complicate predictions. Analyses of long-term air transport price trends in Spain indicate relative stability, with minor seasonal variations (NSI 2024a, b). Studies, including OECC-INECO (2021) and Ecologistas en Acción (2023), emphasize the importance of modal substitution for emission reductions, focusing on scenarios where high-speed rail absorbs air travel demand. Sensitivity tests explore train substitution rates from 50 to 115%, accounting for potential induced effects from enhanced rail services. These scenarios underline the need for adaptive planning to balance economic, environmental and behavioural impacts of transport mode shifts.

Then, as summarized in Table 2, for each of the scenarios, we measure on the one hand the isolated impact of the reduction in air transport (scenarios 1A, 2A and 3A). Then, the overall impact, assuming the substitution of flights for rail transport, is presented (scenarios 1B, 2B and 3B). The last 3 scenarios are logically more plausible, but we need to consider the sensitivity to price changes and to transport modes (i.e. to what extent this substitution is expected to happen).

In any case, as commented in the discussion of results and in the Appendix with complementary sensitivity tests, the effects of future prices should not be much of our concern, as not only our use of prices has mostly to do with properly obtaining current expenditures and shares involved in the banning of short-haul flights, but also we already work with ranges, with potential variations in prices.

In practice actually, the sensitivity to prices and to the transport mode substitution are not independent aspects (e.g. in the report of the CNMC 2023, based on the consultation to railway users, it is clear that "affordable prices" are needed so that the railway is "a substitute for the car"). Accordingly, in the results, we will also explore the two sensitivity analyses performed together.

Results

Socio-economic effects

Thus, Fig. 2 shows the short-term, ceteris paribus (i.e. without relocation of flights, of workers, or compensation measures, etc.), economic effects in Spain for 2023. The intervals or error bars show the variability of the results, related to price variation (in red, which is explained in the data availability section and in Annex 1), variability in transport mode substitution (in purple) and a combination of both in orange. Note that in the case of train substitution, in addition to the price effects, the changes in passenger behaviour explained above have also been considered, making the margin of error larger. If we focus directly on the results of scenario B (with the substitution, not just the "pure" air transport reduction effect), in the case of the first scenario, the losses in terms of output would be in the range of 134 to 201 million €, 32–71 million € in terms of value added and 1298–1328 in jobs. The losses in the second scenario would be in the range of 250–474 million € in terms of output, 43–235 million € in value added and 2909–4256 jobs. Finally, in the third scenario 377–706 million € in output, 68–347 million € in value added and 4311–6265 jobs would be lost in Spain.

However, not all of these losses would be in the aviation sector. The input–output methodology allows looking at value chains in order to see the impact on all the productive sectors involved in the final products and services. Thus, of the negative impacts mentioned in Fig. 2, around 60% of the impacts mentioned would be in the aviation sector. The rest of the most affected sectors in Spain (that form part of the aviation value chain) and their relative weights are shown in Table 3. Nevertheless, it should also be considered that by including the substitution by train for these passengers (scenario B), these negative impacts on the other sectors of the value chain can be mitigated (fully or partially), as they support the rail sector. Particularly relevant in this respect is the case of the warehousing and support activities for transportation, as being the most affected sector besides aviation by the ban on air routes, it would mitigate more than the total negative impacts with rail substitution. This means that by including the substitution by rail the negative effects created

Table 2 Summary of Scenarios and variants (baseline and sensitivity tests)

Scenario	A. pure flights elimination effect	B. Expected air for train and other modes of transport Substitution
1. 2:30 hours limit 2. 4:00 hours limit (current routes) 3. 4:00 hours limit (including feasible routes in the future)	Baseline, with sensitivity to estimated prices (*Interval or error bars in red in Figure 2)*	Baseline, with sensitivity to estimated prices (*Interval or error bars in red in Figure 2)* and sensitivity to expected transport mode substitution (*interval or error bars in purple)*

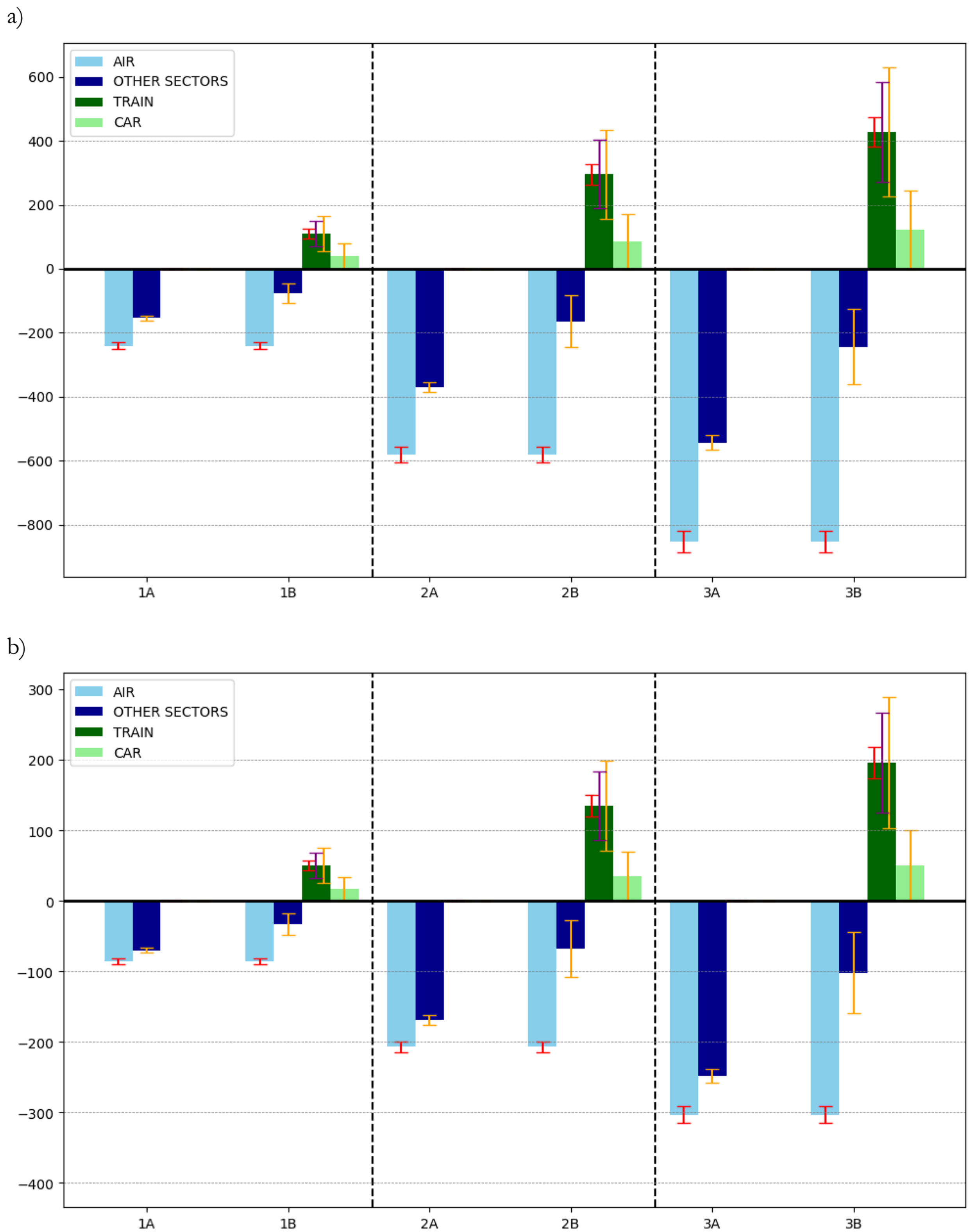

Fig. 2 Effects on output (panel **a**) and value added (panel **b**) of the three scenarios without (scenarios **A**) and with train substitution (scenarios **B**), plus sensitivity analyses to price variation and modal substitution (in million euros). * Interval or error bars in red show the sensitivity to estimated prices, interval or error bars in purple show the sensitivity to expected transport mode substitution and the interval or error bars in orange show the combination of both. The interval for the car also includes the sensitivity to the number of passengers in the car. Note that in the case of the other sectors, the impact will vary only by the price variation in the **A** scenarios but will also be affected by the expected substitution variations in the **B** scenarios

by the ban would be completely eliminated and additional positive effects related to rail transport would be created in this sector. At the other extreme among the most affected sectors in Spain are the rental and leasing activities and manufacture of other transport equipment sectors, where only 4.9% and 2.5% of negative impacts would be mitigated, respectively. Thus, as can be seen in Fig. 2, between 60 and 87% of the negative economic effects in the value chain of other sectors would be mitigated including substitution by rail, albeit with sectoral restructuring.

The "Warehousing and support activities for transportation (H52)" is then the most affected sector (a stronger supplier than to the train activity), notably in Spain, which has as main input the "catering" activities (driving also strong demand from agri-food sectors in Spain). We may also highlight domestically "Rental and leasing activities" and the "Manufacture of other transport equipment" also as stronger input than for railway. In addition, in a global economy, the ban would also have an impact on other countries, especially in a sector as international as air transport. Thus, multiregional input–output tables allow the analysis of international value chains to analyze where the impacts would occur. In this case, the most affected countries include, in this order, Great Britain, the United States, France, Germany and China. In these countries, in addition to the airline industry itself, other sectors of the value chain would be affected, such as warehousing and support activities for transportation (H52), manufacture of other transport equipment (C30) or extraction of crude petroleum and services related to crude oil extraction (B06).

Greenhouse gas emissions

In terms of CO_2 emissions, in 2023, the first scenario would reduce between 170 and 186 thousand tonnes in the Spanish air sector, and an additional 16–18 thousand tonnes in the rest of Spanish sectors in the value chain (i.e. a central total of 195 thousand tonnes of reduction). CO2 emission reductions would reach between 350 and 389 thousand tonnes in the second scenario (410–445 thousand tonnes in the aviation sector itself) and 551–662 thousand tonnes in the third scenario (602–654 thousand tonnes from the aviation sector). Thus, in the first scenario aviation emissions would be reduced by 1.68–1.84% and 4.07–4.41% in the second and 5.97–6.48% in the third. Looking at the scenarios B, depending on the mode of substitution of these passengers, in the first scenario the total emissions reduction in Spain would be between 99 and 184 thousand tonnes. In the second, between 238 and 435, and in the third, 351–639 thousand tonnes. We may also realize that compared with the first scenario (2:30 h limit), the second scenario (4:00 h limit) achieves a much larger reduction of emissions—by a factor of 2.4 (computed as 470/195 in scenario A or 336/141 in scenario B) (Fig. 3).

Moreover, as it was mentioned in the introduction, emissions of pollutants other than CO_2 are at least as important as CO_2 emissions in the aviation sector. Therefore, emission reductions of other GHG have also been considered, such as methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF6), 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).

When considering total emission reductions in Spain, including the substitution by train (scenarios B) does not shown such a maximum of reduction of emissions (as scenario A), as this economic activity also produces emissions. However, apart from being more realistic the scenario B (with is variants/sensitivity analysis) considering that the objective is to reduce emissions as much as possible while affecting the economy as little as possible, the results including the rail alternative are significant. One way to see this is for example that the change in the CO_2 emissions to output multiplier (CO_2/Output) with respect to the baseline is the following:

	1A	1B	2A	2B	3A	3B
% change in the CO_2/Output multiplier	−49%	−135%	−49%	−178%	−49%	−146%

Interestingly, it seems that in terms of the multiplier, the scenario that achieves a higher environmental benefit per output loss is scenario 2B. Another way to see is calculating the % change in GHG emissions to % change in Output ratio, where being above 1 means that the percentage reductions of that pollutant is greater than the economic loss, being larger the larger the value (the all cases in total the % changes both in emissions and output are negative, showing a positive ratio). As can be observed in Table 4, in that positive direction of larger environmental reduction than output loss, very relevantly are found the results for CO_2, N_2O, NOx, NH_3 and CO, as the mitigation of negative economic effects is much more relevant than the emissions produced by this activity (while in some other cases such as SOx and the fluorinated gases this is not the case).

As mentioned before, the planned, and simulated here, policies and measures may lead to changes in the behaviour of passengers who do not necessarily switch to the train. The before mentioned report by the French Ministry of Ecological Transition (Ministère de la Transition Écologique, 2023) shows data on what modes of transport passengers who actually stop using air transport use (63% train, 30% car, 7% choose not to travel).

It is possible to think that the aforementioned central assumption, which considers a 30% substitution of flights

Table 3 Most affected sectors in Spain (NACE classification) besides air transport (output loss)

Sector	Weight on total impacts	Mitigation with train alternative
Warehousing and support activities for transportation (H52)	8.4/8.6%	133.6/139.2%
Manufacture of coke and refined petroleum products (C19)	4.6/4.8%	34.8/36.4%
Rental and leasing activities (N77)	4.0/4.1%	4.9/5.5%
Manufacture of other transport equipment (C30)	2.0/2.1%	2.5/2.9%
Telecommunications (J61)	1.9/2.1%	16.1/18.2%

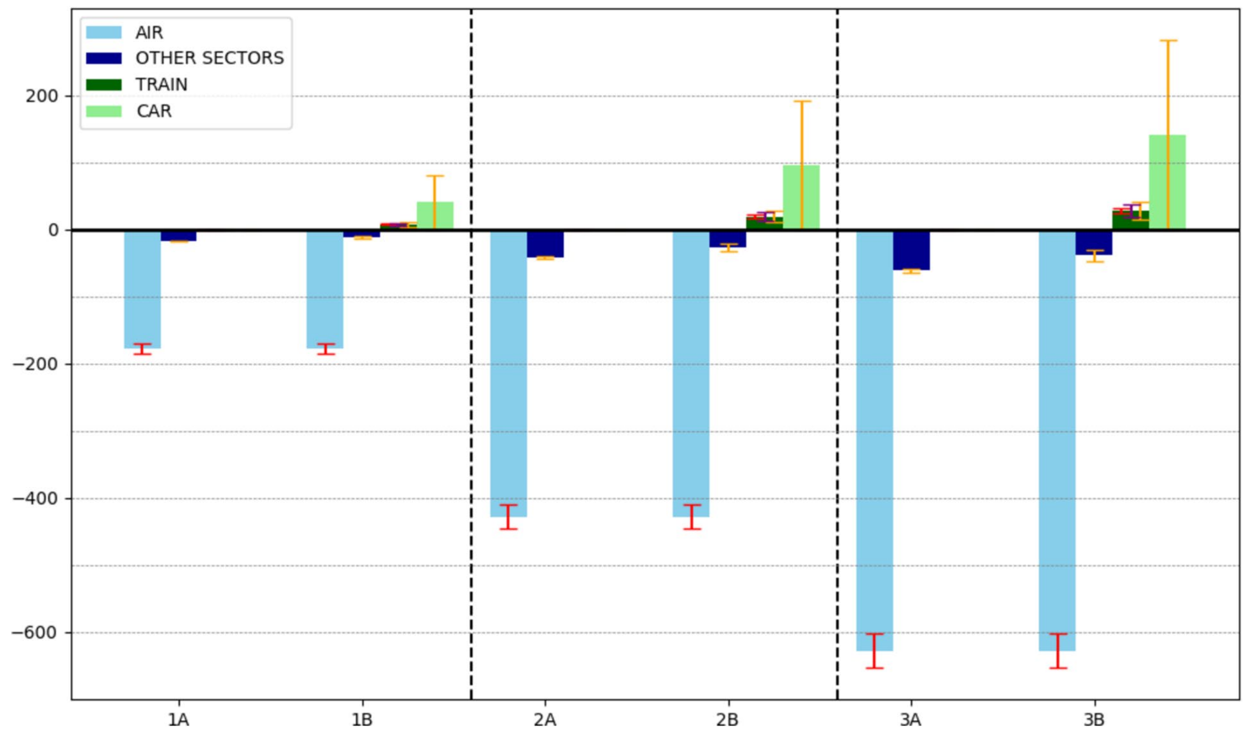

Fig. 3 Effects on CO_2 emissions (in thousand tonnes) of the 3 scenarios without (scenarios **A**) and with train substitution (scenarios **B**), plus sensitivity analyses to price variation and modal substitution. * Interval or error bars in red show the sensitivity to estimated prices, interval or error bars in purple show the sensitivity to expected transport mode substitution and the interval or error bars in orange show the combination of both. The interval for the car also includes the sensitivity to the number of passengers in the car. Note that in the case of the other sectors, the impact will vary only by the price variation in the **A** scenarios but will also be affected by the expected substitution variations in the **B** scenarios

by car, underscores the efficacy of trains as a commendable mode of travel (Cantos-Sánchez et al. 2023; Cantos-Sanchez et al. (2024) even question the net benefits in terms of welfare and environmental damages if as a result of the bans car traffic notably increases—together with increases in international flights and train ticket prices). The Spanish Ministry for Ecological Transition (IDAE 2024) though provides a comparative analysis of CO_2 emissions by mode of motorized transport per passenger-kilometre, revealing emissions of 192 g for aviation, 121 g for cars and 23 g for the AVE (high-speed train). The data of the Spanish Ministry underscores a stark contrast between aviation and high-speed rail emissions, while the difference between aviation and cars is less pronounced. While based on that it may be argued that substituting cars for air travel could also contribute to reducing emissions, the data clearly indicates that the most substantial environmental impact lies in shifting passengers from planes to trains.

Even more, the range of results provided here, including the common approach so far taken in this type of analysis for Spain (OECC-INECO 2021; Ecologistas en acción 2023) of assuming a 100% substitution by train, and even the 115%

Table 4 % change in GHG emissions/% change in Output for high-speed train and flight comparison

	Pollutant									
	CO_2	CH_4	N_2O	SOx	NOx	NH_3	CO	SF6	HFC	PFC
Scenario 1A	7.07	0.95	15.57	0.86	9.91	20.62	10.78	0.29	0.27	0.23
1B	19.26	1.51	44.86	0.64	25.46	61.31	30.29	0.54	0.45	0.47
2A	7.07	0.95	15.57	0.86	9.91	20.62	10.78	0.29	0.27	0.23
2B	25.50	1.80	59.86	0.53	33.43	82.15	40.28	0.67	0.54	0.60
3A	7.07	0.95	15.57	0.86	9.91	20.62	10.78	0.29	0.27	0.23
3B	20.94	1.59	48.91	0.61	27.61	66.93	32.98	0.58	0.48	0.50

scenario, reveals more notably such potential of the train, particularly in contexts where the primary policy aim is the mitigation of emissions through this means of transport (as it is the case when basing it on a "reasonable" train alternative time).

Discussion and conclusions

Transport, and especially aviation, remains a sector with ample room for improvement in the area of environmental impact mitigation (see also the aviation and climate change adaptation literature review of Ryley et al. (2020)). Measures such as the one proposed by the Spanish government (and its French counterpart, already implemented) seek to reduce emissions in the sector where the rail alternative is feasible. Thus, this study aimed to quantify different alternatives for implementing the measure in order to be able to analyze its socio-economic and climatic impacts. Pre- and post-COVID-19 data for domestic air transport already show significant changes in aircraft models in pursuit of energy efficiency. In addition, having exceeded the pre-COVID number of total domestic air passengers, the routes which could fall under the ban indicate a downward trend in both the number of flights and passengers; hence, this decrease in short-haul flights is already taking place without the ban.

Along these lines, we explored different levels of implementation depending on the corresponding train alternative time (scenarios 1 to 3), with the "pure" effects of aviation reduction (scenarios A) and the consideration of such effect and that of the modal substation (mainly with train, given the nature of the policy, represented in scenarios B), including around this scenario B additional sensitivity analyses to price variability and modal substitution (given the uncertainty around potential behavioural changes). With the "pure" reduction effect of scenario A, apart from very noticeable environmental benefits, the input–output analysis shows significant negative socio-economic impacts, both for the aviation sector and its value chain. But by including rail substitution, however, between 60 and 87% of the negative impacts on the value chain would be mitigated.

In particular, in terms of CO_2 emissions, in 2023, the first scenario would reduce, depending on the mode of substitution of these passengers, between 99 and 184 thousand tonnes in Spain. In the second scenario, between 238 and 435, while in the third, between 351 and 639 thousand tonnes. Socio-economic impacts are also explored, finding that the first scenario would reduce output between 134 and 201 million euros in the Spanish economy. In the second scenario, there would be 250–474 million euros reduction considering all sectors, and in the third scenario, 377–706 million euros. The % change in GHG emissions to % change in Output ratio is also explored, finding noticeable large ratios above one in the results of CO_2, N_2O, NOx, NH_3 and CO, as the mitigation of negative economic effects is much more relevant than the emissions produced by this activity (while in some other cases such as SOx and the fluorinated gases this is not the case).

Going more into the policy context and implications, we may highlight that the high-speed rail sector has reached unprecedented levels of patronage, evidenced by surges in both passenger volumes and available seating capacities, primarily attributed to the phenomenon of market liberalization and the influx of new competitors. Subsequently, the advent of these new market players has precipitated some decline in fare rates, thereby rendering this mode of transportation increasingly appealing to consumers. Such measures align closely with the transport objectives outlined by the Spanish government, given the concurrent expansion of supply within the high-speed rail domain, as previously delineated. Moreover, substantial investments are being directed towards the augmentation of high-speed rail infrastructure, further substantiating the government's commitment to fostering the development and utilization of this mode of transportation. These investments are key and can play a fundamental role in changing passenger behaviour in order to redirect them to high-speed rail, as is the objective of the measure. To accommodate the anticipated influx of new passengers, it is essential to consider increasing the frequency of rail services. Such measures would not only support the greater volume of travellers but also mitigate the risk of individuals substituting air travel with other less sustainable forms of transportation, such as personal vehicles.

Banning can be compared to carbon taxes in several dimensions: behavioural flexibility (taxes offer more to individuals), speed of impact (taxes rely on more of gradual behaviour shifts and technological improvements), social and economic equity (e.g. on groups, regions or industries affected), etc. But it seems clear that both approaches are more feasible where high-speed rail or other efficient, low-carbon options are available. Also, both can encounter significant challenges, particularly in gaining public support and mitigating economic impacts (Jagers et al. 2019). To address these challenges, compensatory measures have been proposed as complementary to bans or carbon tax policies. These measures are designed to offset the costs associated with these policies, enhance public acceptance and ensure the overall effectiveness of carbon pricing mechanisms (Geroe 2019). If applied, compensatory measures may involve carbon tax revenues redistribution to support the transition to more sustainable practices (Becattini et al. 2021). Revenue generated from carbon taxes could be invested in research and development of sustainable aviation fuels or carbon capture technologies, thereby enabling the industry to reduce its carbon footprint while maintaining economic viability. Then, the airline sector may undergo another (after recovery from the COVID-19 crisis) restructuring.

The choice of adoption of one or the other scenario proves to be very relevant, as the second scenario (the one that based on the change in the emissions to output multiplier achieves a higher environmental benefit per output loss is scenario 2B) increases the reduced emissions of the first scenario by a factor of 2.4. Moreover, the train proves to be an excellent alternative for the emissions reduction objective, as it produces very low emissions in relative terms. Thus, the train emerges as the most viable alternative for achieving significant emission reductions, unlike the car, where these environmental benefits are considerably diminished. This highlights the critical role of rail transport in advancing sustainable mobility and underscores its superiority in meeting emission-saving objectives compared to other motorized transport options. Hence, it is evident that these measures are in nascent stages, suggesting a requisite period of adjustment. Beyond the airline sector, the rail industry will likewise need to undergo adaptations to effectively accommodate the surge in demand and sustain its appeal to passengers. Enhancements in infrastructure and technological capabilities within are imperative for such policy. This involves obviously the companies offering the railway services and the public sector. We have seen that ADIF (2024a, b), the public company that manages the operation of Spain's railway lines, shows quite clear plans on current and new infrastructure construction. Our exploration has focused though on railway infrastructure that is already finalized, or close to be finalized, or with clear-cut advances already in the implementation (considering also the connection with cities having nearby airports, etc.) because the environmental damages (not only of GHG emissions but also of materials, minerals, etc.) and effects of the construction period tend to be high (see Bueno et al. (2017); Kortazar et al. (2021); Damián and Zamorano (2023)).

Future research could examine the environmental and economic impacts of implementing these measures across diverse national and international contexts. Such studies would offer valuable insights into the broader applicability and effectiveness of these strategies, providing a foundation for scaling them up in a manner that is both sustainable and economically viable. This analysis would contribute to a more comprehensive understanding of the potential benefits and challenges associated with widespread adoption of the short-haul flight banning. For the particular case of Spain, we envisage that the studies may go in four directions: first, further exploring the economic and environmental costs and implications of new high-speed train construction (for potential additional extensions of the measure); secondly, further exploring the demand diversion and induced effects through an integrated transport mode choice model (see, e.g., DT, 2014; Meixell and Norbis, 2008); thirdly, comparing the effects of the banning with alternative (tax, stick/carrot policies); fourthly, ex-post evaluating the effects of the measure if finally implemented.

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