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Airlines' Network Analysis on an Air-Rail Multimodal System

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Abstract

This article explores the potential impact of short-haul flight bans in Spain. We build the rail and flight network for the Spanish peninsula, merging openly available ADS-B-based data, for the reconstruction of air schedules and aircraft rotations, and rail operator data, for the modelling of the rail network. We then simulate a ban that would remove flights having a suitable train replacement, *i.e.,* representing a trip shorter than a threshold that we vary continuously up to 15-h. We study the impact in terms of 1) air route reduction, 2) aircraft utilisation and fleet downsizing for airlines, 3) airport infrastructure relief and rail network requirements, 4) CO_2 emissions and 5) possible itineraries and travel times for passengers. We find that a threshold of 3 hours (banning all flights with a direct rail alternative faster than three hours) presents some notable advantages in emissions while keeping the aircraft utilisation rate at an adequate level. Interestingly, passengers would then experience an increase in their itinerary options, with only a moderate increase in their total travel times.

Keywords: multimodality; modal shift; network analysis; airline fleet; emission reduction

Abbreviations: SIBT: Schedule In-Block Time, SOBT: Schedule Off-Block Time

1. Introduction

The route network is a key airline asset that defines its market and resource allocation. Main network models are point-to-point (usually used by low-cost airlines) and hub-and-spoke (traditionally operated by legacy airlines and airline alliances); the latter increases the airline's potential connectivity, as the short-haul flights bring passengers to a hub where they are distributed to onward flights (often long-haul ones). However, short-haul flights are less fuel efficient per passenger-km performed [1], thus creating a higher environmental impact. European mobility strategy calls for green, smart and affordable mobility [2], calling for emissions reductions across transport modes and multimodality. In that context, railways are becoming an important part of the transport network as their emissions are lower and, in the context of door-to-door mobility, they offer easy access due to the city-centrality of rail stations. These characteristics point to the possibility of replacing certain flights by rail, reducing the emissions, to be balanced out by the high level of connectivity offered. For example, policies such as banning short-haul flights in France have very limited impact [3] on emissions as connecting fights are except. A similar policy is part of the governance arrangements for the potential coalition Spanish government, driving a *reduction* on domestic flights when suitable, faster than 2.5 hours, rail alternative is available, but still excluding flights with international

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connections [4]. If more ambitious policies are to be implemented, the multimodal analysis of the remaining network, focusing on connectivity, is required [5].

The substitution of flights by rail alternatives in a disjointly planned rail-air network would impact passengers' connectivity and travel time; airlines should re-design their fleet assignment to account for removed flights; airports would experience modified demand for operations, and rail operations would need to provide capacity for additional passenger demand. Thus, any new policy should be informed by the appropriate analyses.

Modal choice studies are not new, and the substitution potential of air and rail has been addressed, with travel time and frequency being among the most relevant factors determining travel behaviour [6, 7]. Another important factor is the environmental impact of different transport modes. For example, Avogadro et al. analysed air and rail route substitutability in Europe and found that when the main factors are travel time and costs, substitution could reduce emissions by about 5% [8].

As discussed, any analysis of substitution or cooperation between air and rail needs to assess the impact of the changes on the operators' networks, infrastructure requirements, passenger connectivity, and travel times. Despite the interest in this paradigm, until recently, it has been difficult to carry out these types of analyses due to the lack of public and integrated datasets for railway and airline services in Europe. New data-sharing initiatives in the rail community are arising, such as the release of datasets, including rail timetables, by Renfe, the main Spanish rail service provider [9]. Due to the economic sensitivity of schedules and fleet usage, airlines are reluctant to share equivalent datasets covering adequate periods [10].

Research contribution. The research presented here analyses a case study of full-mode substitution between air and rail applied to operations within Spain. The goal is to assess the impact of substituting flights impacted by a banning policy and airline fleet reorganisation, potential passenger connectivity changes, travel times and total emissions estimation.

As the available data allows assessing different assumptions, we consider a particular form of substitution: *flight/s which operate on a route served by at least a train faster than a given threshold (0-15 hours) are banned.*

The case study centres on airlines' operations with flights within Spain considering their alliances enabling passengers' connectivity and itineraries[1]. OpenSky data [11] is used to approximate airlines' schedules and track the aircraft to model their fleet utilisation, and Renfe data [9] to model the rail network. In Section 2, the data sourcing and preparation and methodology applied are presented before describing the results in Section 3. Finally, conclusions, future work and limitations of the data are discussed in Section 4.

2. Data and approach

This section covers the data and methodology used. We start by describing the data sources and the needed data cleaning and preparation for the case study. We then describe the methodology applied in the case study. We will analyse the impact of introducing a flight ban in Spain, which eliminates the flights operating routes served by rail faster than a given threshold. We will explore the impact of these thresholds by ranging them from zero (no-ban) to 15 hours at 15-minute intervals for particular days in May 2023.

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[1] Itinerary consists of one or more flights (and trains) between an origin-destination pair.

2.1 Data description and preparation

A week of air traffic in May 2023 has been used in the analysis, with flights arriving/departing from the 1st to the 7th of May 2023, to, from and within Spain. Note that some flights might depart on the 30th April or land on the 8th of May. Further, the 1st of May is a public holiday in Spain, and the 2nd May is a public holiday in the region of Madrid. This week has been selected as it is a busy week in spring. We expected that public holidays might impact rail service availability; however, after analysing the dataset, we found a similar number of rail services daily. Using a week, instead of a single day, enabled us to capture air services not provided daily within Spain. As we focus on potential mobility, *i.e.,* potential flight and multimodal itineraries that passengers could use, and not on the actual demand, results can be considered generic enough to represent the typical possible mobility within Spain. Results are expected to be stable due to the characteristics of the Spanish air and rail network (with air hubs in Madrid, Barcelona and Malaga, and a radial high-speed network to/from Madrid), as shown in Section 3.1. Further analysis, including passenger demand, should be performed considering different periods of the year to capture potential demand season patterns. Table 1 summarises the different data sources used for the analysis, while the particular data cleaning and preparation is described in the following sections. All data used can be accessed from [12].

Table 1. Data sources

Data name	Description	Scope	Provider
Flight data 4	Table from OpenSky historical database with basic flight information per flight	Worldwide	OpenSky [11, 13]
Aircraft database	Table with information on aircraft (transponder Id, registration, model, etc.)	Worldwide	OpenSky [11, 13]
Trips	Information on train *trips*. A trip is a given train service following a set of stops at defined times. A trip is for a given route and service	Spain	Renfe [9]
Stop times	Lists of stops with stopping times per trip	Spain	Renfe [9]
Routes	Information on routes by rail services. Different trips might use the same route, stopping at the same or different stations. Routes are classified by the type of rail service, *e.g.,* AVE, Regional, Intercity	Spain	Renfe [9]
Calendar	Dates of the week in which services are run between given dates	Spain	Renfe [9]
Stops	Information on stops (stations)	Spain	Renfe [9]
Rail fleet	Information on seats per rail service	Spain	Renfe [14]
Ecopassenger	Information on emissions per rail service	European	International Railways Union [15]
Airports (a/p)	Airports' coordinates	Worldwide	Collected by the authors [16]
A/p manually modified	List of airport codes swapped as erroneous departure or arrivals, explained in Section 2.1.1.	–	Generated by the authors [16]

2.1.1 Airline network data preparation

First, using the data from OpenSky (*flight data 4*), we identified the airlines operating commercial flights within Peninsular Spain, as these could be potentially replaced by rail. Thus, only flights operated by these airlines are considered in the analysis: Vueling (VLG), Ryanair (RYR), AirNostrum (ANE), AirEuropa (AEA), Iberia (IBE) and IberiaExpress (IBS). To use the data in this case study, it still needed to be cleaned and prepared.

Despite the improvement in identifying the departure or arrival airports of flights (in the *flight data 4*) by OpenSky, they are still often erroneously identified[2]. The errors are generated due to the potential loss of ADS-B traces near the ground in some regions. For example, the small airfield of Lucca (LIQL), which cannot accommodate passenger aircraft, is recorded as the destination of a commercial flight instead of the nearby International Airport of Pisa (LIRP). By manually exploring these cases and using domain knowledge, 61 airport substitution pairs are defined by the authors. The airport substitutions list is available in [16].

Further checks were performed, as aircraft rotations[3] were broken in some cases. For example, an aircraft arrives at airport X, but the same aircraft departs subsequently from airport Y, or an aircraft with arrival/departure to an unidentified destination (NULL). An algorithm has been developed to correct these rotations. The process is as follows (for each aircraft where the arrival and departure of subsequent flights do not match):

1. If in one flight one of the airports is not identified in the dataset, *i.e.,* recorded as NULL, the code of the one available is used instead.
2. If both airports are identified in the *flight data 4* dataset but are different, *i.e.,* the arrival and subsequent departing airports differ, and these airports are located at a great circle distance > 80 km, a new flight between those airports is added if:
   (a) there have been historical fights operating between those two airports,
   (b) the average flight time between those airports is greater than one hour, and
   (c) the time between the two flights is greater than the average flight time between the airports plus two minimum turnaround times[4] (defined as 50 minutes) to ensure enough time for this extra flight to be added.
3. If both airports in a turnaround are identified but different and close by, great circle distance ≤ 80 km, one is assumed to be mislabelled. The airport with the most operations is considered the most likely, and the other airport is replaced accordingly.

A total of 801,020 flights were processed for the week of May 2023, 799,527 of which have a call sign, and 30,114 flights are from one of the airlines of interest (VLG, RYR, ANE, AEA, IBE and IBS) (3.8%). The sourced flight data covers 26 airports within Peninsular Spain with flights (96 routes, *i.e.,* origin-destination pairs). Over the 30,114 flights considered, 0.3% of the departures (80) and 1.1% of all the arrival airports (338) are manually modified; and, as part of fixing the rotations, 4,905 departure and 5,035 arrival airports are further changed, with only three flights added.

Finally, OpenSky provides *first seen* and *last seen* for each aircraft. These correspond to the start and end times of the ADS-B traces. We need, however, the scheduled times (Scheduled In-Block Time (SIBT) and Scheduled Off-Block Time (SOBT)). These are estimated in the following way: the dataset also contains information on the aircraft's altitude at the first and last points of the trace; therefore, we estimate the take-off and landing time by assuming a constant climb speed of 2,000 ft/min and a descend vertical speed of 1,500 ft/min, which are *nominal* performance values. Note that the route time is, therefore, composed of the ADS-B traces and eventual additions for the estimates of the initial climb and final descent segments (if missing).

According to EUROCONTROL taxi times reported data for summer 2021 [17], the average taxi-out time for all airports in Spain was 10.6 minutes, with a maximum average value of 15 minutes for Barcelona (LEBL). On average, across all airports, the 90^{th} percentile taxi-out time was 14 minutes, with a maximum of 23 minutes for Madrid (LEMD). The reported average taxi-in time for all Spanish

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[2] This is true at the time of the writing for the data used

[3] A rotation is a sequence of flights performed by the same aircraft.

[4] Time between arrival and departure by an aircraft.

airports was 4.8 minutes (9.1 minutes for LEMD and 5.5 minutes for LEBL), with an average 90^{th} percentile of 7 minutes. With these considerations, we subtract from the estimated take-off time 20 minutes for taxi-out and add 10 minutes for taxi-in times to estimate the departure and arrival block times. Even if more accurate values could be used, selecting 20 minutes for taxi-out and 10 minutes for taxi-in ensures that the block times are usually within these estimates. The potential overestimation of taxi times could also account for some schedule padding, which is not possible to estimate with the OpenSky data.

2.1.2 Rail network data preparation

Renfe (Spanish Public Rail Service Operator) provides an open dataset containing information on long and medium-distance rail services for high and conventional speeds. These data are processed to extract all possible direct rail trips between the airports in Spain.

A set of stations within a 25 km radius are identified for each airport. Then, instead of considering only rail services between cities linked by direct flights, the direct rail services for all origin-destination combinations are identified (529 pairs) for each day. In total, close to 340k (rail) station-to-rail station pairs are analysed. This allows us to consider direct trains that replace passenger itineraries on connecting flights.

The rail services obtained are filtered so that the most suitable origin-destination rail station between each origin and destination airport pair is kept, *i.e.,* the trains which use the main stations from all the ones close to the airports. After this process, a daily average of 1040 train services are obtained, with between one (for most) and three (for Madrid) rail stations per airport.

2.2 Methodology

To assess the impact of the substitution, which we will term ban from here on, we apply several steps: flight replacement; fleet usage estimation; airport usage; emissions calculation and potential passenger itineraries computation.

Flight replacement. We want to apply an incremental ban on flights. For this, we set a threshold in time (for instance, two hours), and we ban all flights between two cities connected by at least a train, which makes the trip under the time threshold. The fastest train service is filtered for each origin and destination pair to detect such a train. For instance, with a two-hour threshold, all flights between Valencia (LEVC) and Madrid (LEMD) are removed as the fastest train between the cities takes 1h50. Note that to detect the faster train, the day is not considered, *i.e.,* the fastest train on all analysed days is used.

Fleet usage estimation. When considering the fleet utilisation of an airline, all the sets of aircraft rotations performed in a day need to be considered. Figure 1 shows a basic time-space diagram with an example of the rotation where six flights are assigned to a given aircraft (with five turnarounds). We use the notation 1 - 2 - 3 - 4 - 5 - 6 to represent the flights and rotations in a simple manner. An aircraft rotation for the entire day is a set of flights ($j \in A$) flown by the same aircraft chronologically in a given period. This accomplishes two conditions, given two consecutive flights $j - k$: i) the arrival airport of flight j is the departure airport for flight k, ii) the SIBT for the arrival flight j is smaller than the SOBT for the departing flight k. The aircraft rotation problem [18] consists of formulating the tours for the entire airline fleet to cover once and only once each flight, minimising costs and satisfying all the operational requirements, which could include visiting the maintenance base, minimum turn around time, respecting commercial schedules, etc.

Considering the tracking of each aircraft rotation when evaluating the impact of removing flights due to a ban is important, as gaps can be generated. In the example of Figure 1, if flights 3 and 4 are removed, the resulting rotation pattern becomes 1 - 2 - 5 - 6. Therefore, if nothing is done,

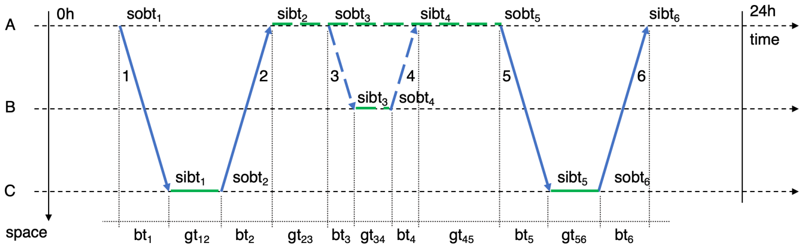

Figure 1. A simple aircraft rotation problem.

the corresponding block times (bt_3 and bt_4) are transferred to a new ground time (gt_25), which is calculated as the difference between the *SOBT* of flight 5 and the *SIBT* of flight 2. The ground time is, therefore, the time that the aircraft spends at the airport, which can be larger than the strict minimum turnaround time required.

Based on these concepts, three metrics are used in this paper:

- Fleet utilisation: the ratio between the sum of the total block times for all the rotations and the total available fleet time (we consider 24 hours per day and aircraft used in this study).
- Variation of ground time: the ratio between the increment of the total ground time divided by the total ground time used as a reference value (this is the total ground time for the original scenario, corresponding to the ban time equal to zero). Ground time does not consider the sleeping time of the aircraft – from the end of the last and start of the first flight in consecutive turnarounds.
- Fleet size: we estimate the new fleet size requirements considering the origin-destination pairs removed by the ban. If airlines can re-assign the fleet, considering also re-scheduling and re-composition of their fleets, assuming as a target to maintain the original utilisation factors, a strategic re-sizing of fleets can be done. A continuous approximation works for strategic purposes, providing a lower bound. The result is obtained as the upper integer of the aggregated block time divided by the utilisation factor and the daily work time window. The resulting number is the best level that can be achieved. In reality, some airlines require different sizes because they serve markets with heterogeneous demand, and this diversification does not let them reduce their fleet sizes more.

Even if not all the flights are impacted by possible bans or operated in Spain, all the flights (30,114) operated by the six airlines of interest are considered for the fleet utilisation analysis, as they are needed to reconstruct the rotations properly.

Infrastructure usage. The flight ban and movement of passengers by rail have two impacts on the transport infrastructure: first, the demand at airports (and airspace) will be reduced. We consider the number of departures and arrivals at Madrid Barajas (LEMD) to indicate this aspect. Second, the seats available on banned flights must be transferred to the rail network. We estimate this additional rail demand with respect to the current supply of seats computed from information on the rail services and fleet composition [9, 14].

Emissions calculation. Air and rail emissions are calculated slightly differently due to the transport mode characteristics and data availability. For air, the analytical model developed by [1] is used to compute CO_2 emissions based on the route's great circle distance and the available seats. This model also accounts for taxi fuel consumption (based on statistical European data, as detailed in [1]). A distance correction is applied to consider that actual routes do not exactly follow the great circle distance. Some aircraft models overpass the limit of the maximum seats considered in the analytical model; in these few cases, emissions were directly calculated using EUROCONTROL's IMPACT tool [19].

The rail CO_2 emissions for seats transferred to rail were obtained from the EcoPassenger calculator [15], which calculates the specific train energy consumption, then considers the energy chain and converts the required energy into CO_2 emissions per passenger. As the emissions are estimated per passenger, only the seats transferred to rail are considered when estimating the additional emissions generated by the air passengers in the rail network. The model feature *maximum load factor* and the option of *national mix of electricity production* were selected.

Possible passengers itineraries. A passenger can use a flight to travel directly between origin and destination but can also use short-haul connecting flights that enable the connectivity of passengers to more destinations. The introduction of air bans might impact the network's potential connectivity from this passenger's perspective. As demand data has not been used, all potential connectivity is computed. This requires, however, some assumptions on which connecting itineraries are possible to avoid generating potential itineraries that would not be suitable, *e.g.,* a connecting flight itinerary with a final destination too close to the origin or for which a suitable direct flight (or train) is available. Some parameters used in the criteria below have been adjusted to ensure that the results obtained as connecting flight itineraries are reasonable. Connecting flights are therefore considered as long as:

- The connection is between flights from the same airline or alliance (IBE, IBS and ANE).
- A minimum connecting time between flights of 45 minutes is used, *i.e.,* the SOBT of the connecting flight must be at least 45 minutes after the SIBT of the inbound flight.
- The origin and final destination of the connecting itinerary are located at least 250 km apart. This is to avoid connecting itineraries where the destination is *too* close to the origin airport.
- There is no direct train between the origin and final destination, or any direct train is longer than 4h30.
- If a direct flight exists between the origin and final destination, the connecting itinerary should not exceed 1.5 times the direct flight alternative.
- If other alternatives (via another connecting airport) are available between the origin and destination, the itinerary is no longer than 1.5 times the median of all other alternatives.
- If the origin and destination airports are in Spain, the connecting airport is not outside Spain.

Finally, suppose the same itinerary with the same airline(s) is available. In that case, the options which minimise the time at the connecting airport are kept, *i.e.,* avoiding long connecting times if an earlier alternative with a lower connection is possible.

Possible rail and multimodal alternatives are computed as flights are removed due to applied bans. This is done by removing the flight (and flight-flight) itineraries impacted by the ban. Then, if direct rail services are available to substitute origin-destinations served by flights (direct flights or flight-flight connections), these rail services are added to the pool of possible passenger itineraries.

Then, with those rail services and remaining flights, multimodal (air-rail and rail-air) possible itineraries are computed considering:

- A minimum connecting time of 100 minutes for rail-air connections and 60 minutes for air-rail connections except for Madrid and Barcelona airports, for which more specific values are used. These have been estimated using Google Maps considering public transport transfer times and, among others, average time between service (15 minutes) and kerb-to-gate times (45 minutes), additional required walking time (10 minutes): Madrid-Chamartin – LEMD (22 minutes by train transfer time) → 85 minutes, Madrid-Puerta de Atocha – LEMD (45 minutes by train or metro transfer time)→ 108 minutes, Madrid-Principe Pio – LEMD (50 minutes by train or metro transfer time) → 113 minutes, and Barcelona-Sants – LEBL (30 minutes by train transfer time) → 93 minutes.

- There is no direct flight between the origin and final destination.

3. Results

The results are structured as follows: first, an analysis of the air routes (and flights) impacted by the different bans is presented in Section 3.2. As explained previously, eliminating flights will impact the airlines' fleet usage; the analysis of these aspects is detailed in Section 3.3. Section 3.4 shows how flight bans translate into air and rail infrastructure demand changes. The environmental impact of these measures and the changes in potential passengers' itineraries are presented in Section 3.5 and Section 3.6, respectively.

The number of flights and rail services within Peninsular Spain varies as a function of the day of the week[5]. Therefore, average values across the seven days will generally be reported, even though connectivity and flight/rail usage differences might depend on the day.

3.1 Spanish air and rail network

As shown in Figure 2a and Figure 2c, the Spanish Peninsular air network pivots around the airports of Madrid (LEMD) in the centre of the country with the hub of Iberia, Barcelona (LEBL) dominated by the operation of Vueling, followed by Malaga (LEMG) and Seville (LEZL). Most of the operations feed Iberia operations; therefore, short-haul flights within Spain mostly follow a hub and spoke diagram with Madrid in the centre. Besides these operations, the distances prevent most of the short-hauls in the same region (*e.g.,* between cities in the south of Spain), and routes operated by low-cost carriers dominate the connectivity of the periphery (*e.g.,* Vueling and Ryanair flights linking the north-west with the east and the north with the south).

From a rail perspective, Spain has developed a radial high-speed rail infrastructure (see Figure 2b) with slower conventional lines linking regions not via Madrid. Therefore, as shown in Figure 2d, it is expected that when rail is used as a substitute for flights, most rail links will be to-from Madrid and only direct rail connections between cities in the periphery are used when the flight ban is significantly large (as presented in Figure 3). As shown, even considering the maximum ban time, not all cities (and air links) can replace any of their flight with direct trains (see, for instance, LEXJ in the north of Spain, which is connected by flight with the south region, *i.e.,* LEZL, LEMG, LEAM, for which direct rail alternatives are not possible).

3.2 Routes replacement

Figure 3 shows an example of four ban thresholds (0h, 3h, 5h and 9h) used to replace flights within Peninsular Spain for a given day (3rd of May 2023). As observed, as the ban increases, the number of origin-destination pairs served by flights decreases while the rail network gains importance. Note that only rail services that could replace routes impacted by the air ban are considered here, as the work focuses on analysing the displacement of passengers from air to rail.

Figure 4 shows the average number of routes (origin-destination pairs) operated per airline and rail services as a function of the ban threshold. Without a ban, on average, 91 daily routes are operated by all the airlines considered[6]. As the ban increases past the 2-hour threshold, the number of routes

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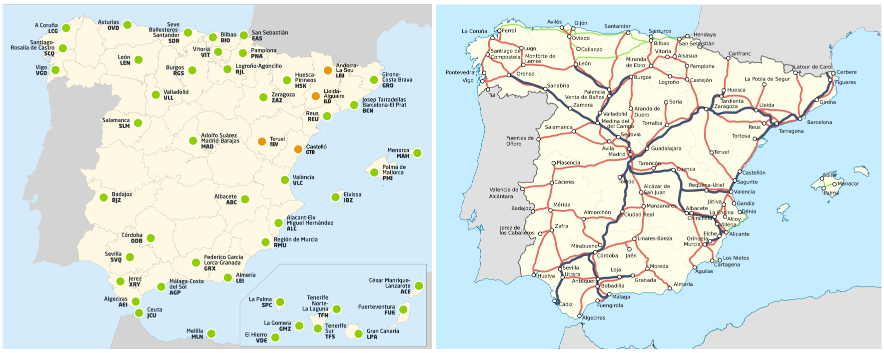
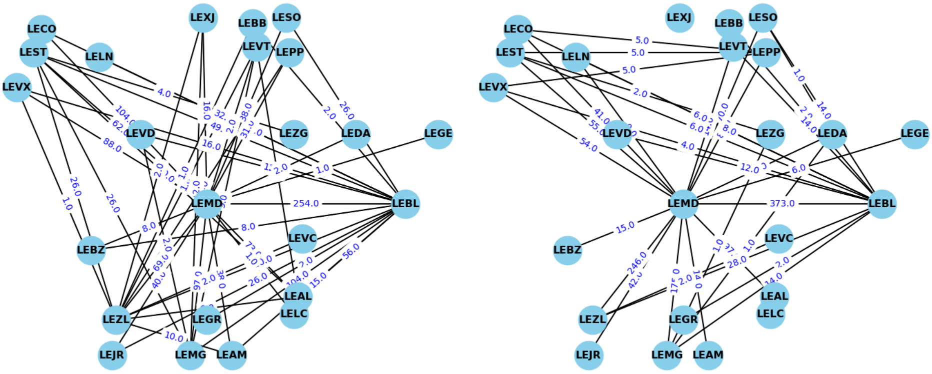
[5] With a mean value of 219 flights and 221 rail services per day.

[6] Considering the same origin-destination by different airlines as different routes. There are 89 unique origin-destinations.



(a) Commercial airports 2022 (green state ownership, orange regional ownership) [20]

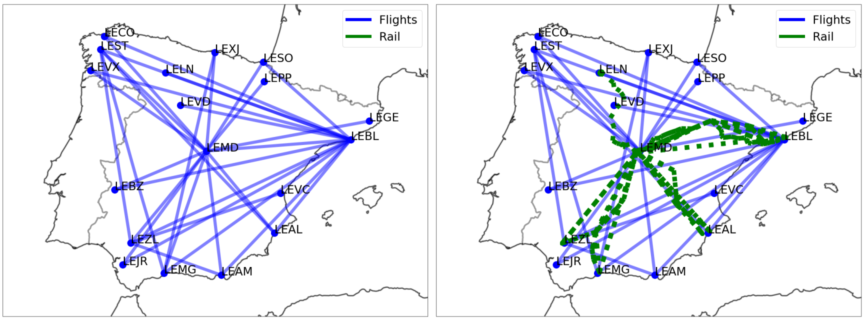
(b) Rail network 2021 (Red: Conventional Iberian gauge, Blue: High-speed lines, Green: Narrow gauge)[21]



(c) Connectivity (number flights 01MAY2023-07MAY2023) between airports in Peninsular Spain

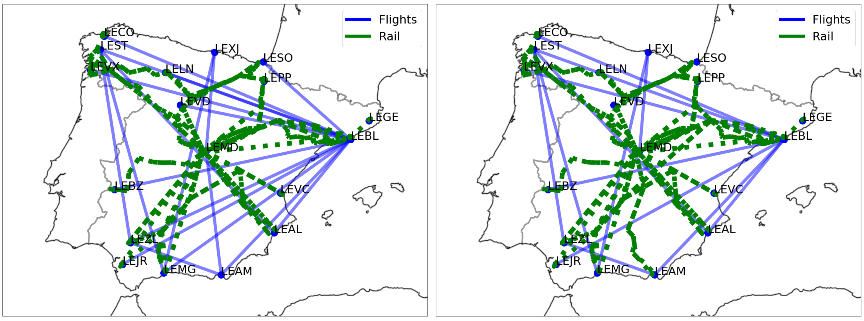
(d) Connectivity (number rail services 01MAY23-07MAY2023) used to replace flights.

Figure 2. Spain air and rail infrastructure and network.



(a) No ban

(b) Threshold ban = 03:00



(c) Threshold ban = 05:00

(d) Threshold ban = 09:00

Figure 3. Example of flights and rail replacement for 03MAY2023 with different threshold bans.

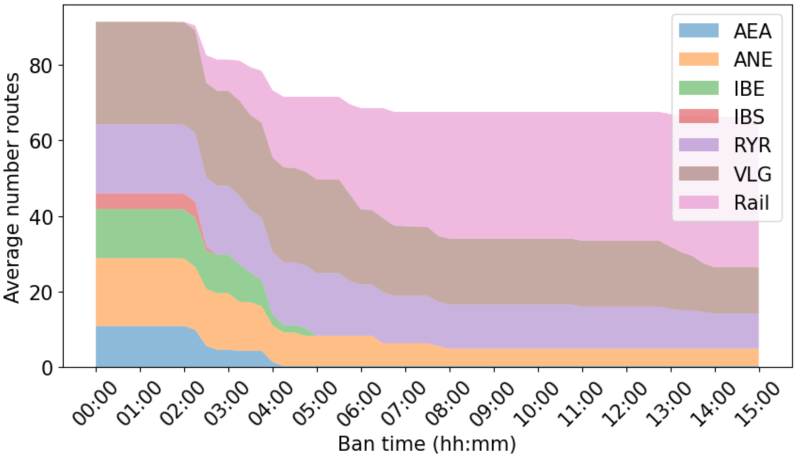


Figure 4. Average number routes per day as a function of temporal air-rail ban within Peninsular Spain.

decreases significantly until the 2h45 threshold, where, on average, 73 routes are covered, with IBS losing its entire network within Peninsular Spain and AEA, reducing from 11 to just five routes. Then, a further reduction in routes is observed up to the 4h15 threshold, when almost all of the routes of AEA and IBE are eliminated. Between 4h15 and 6h15 the reduction in routes is small (from a daily average of 52.9 to 41.6), with most reductions observed in VLG and RYR flights. Increments in the ban threshold produce further reductions. Still, nothing is significantly observed until the 13h point when VLG and RYR routes are further reduced, reaching a minimum daily average of 26.4

routes at 14h. As shown in Figure 3c, with a 5h ban, the high-speed network connecting Madrid with the rest of Spanish cities is fully used. The remaining reduction of flights will be primarily due to the banning flights connecting the periphery of Spain, which is poorly served by rail, *i.e.,* requiring long train journeys of more than 13h. In parallel, the number of origin-destination pairs with suitable rail replacement increases to a daily average maximum of 39.8 routes for a 14h ban. The reduction of routes served by airlines is larger than the rail increment due to the overlap of routes operated by different airlines.

3.3 Fleet usage

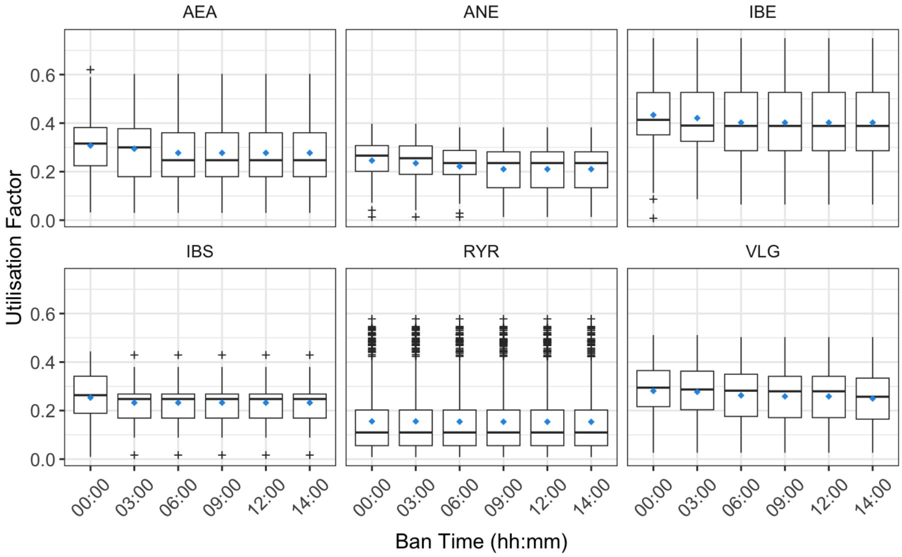


Figure 5. Evolution of airline's utilisation factor with ban time.

As flights are replaced by rail when the ban threshold increases, the number of operated flights decreases from 219 flights per day without a ban to only 36 with a 14h ban. As mentioned in Section 2.2, removing these flights would create *gaps* in the planned rotations and impact the utilisation of airline fleets. The complete set of flights of the airlines (30,114) is used to analyse the factors previously described.

First, Figure 5 shows how the airline's utilisation factor decreases when different ban times are considered and the fleet is not re-assigned to optimise aircraft rotations. This is coherent with the variation observed in the distribution of block times for the six airlines and the different ban times analysed because shorter block times are removed.

Second, the variation of ground time is calculated using only aircraft that operate in the short-haul market, which is more affected by the measure. Figure 6 presents the variation of ground time as a function of the ban threshold. As observed, the variation increases until the 6h ban. For higher ban thresholds, the number of additional flights removed is small. For an airline focused on the domestic market, with limited options to increase or disperse its network, an increment between 20% to 30% of the ground time can seriously impact its profitability.

Finally, Figure 7 shows how the fleet could be reduced when higher ban times are considered, and the fleet is optimised to maintain the original utilisation factor. The potential fleet reduction observed is unimportant in relative numbers for pan-European airlines with dispersed networks such as VLG or

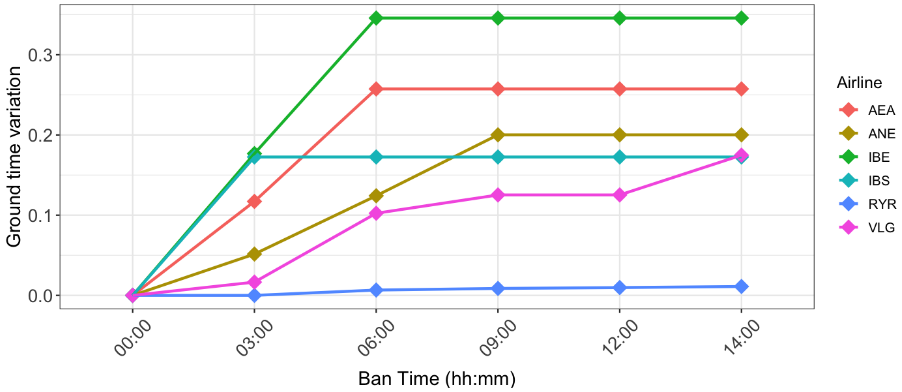


Figure 6. Variation of airline's ground time with ban time.

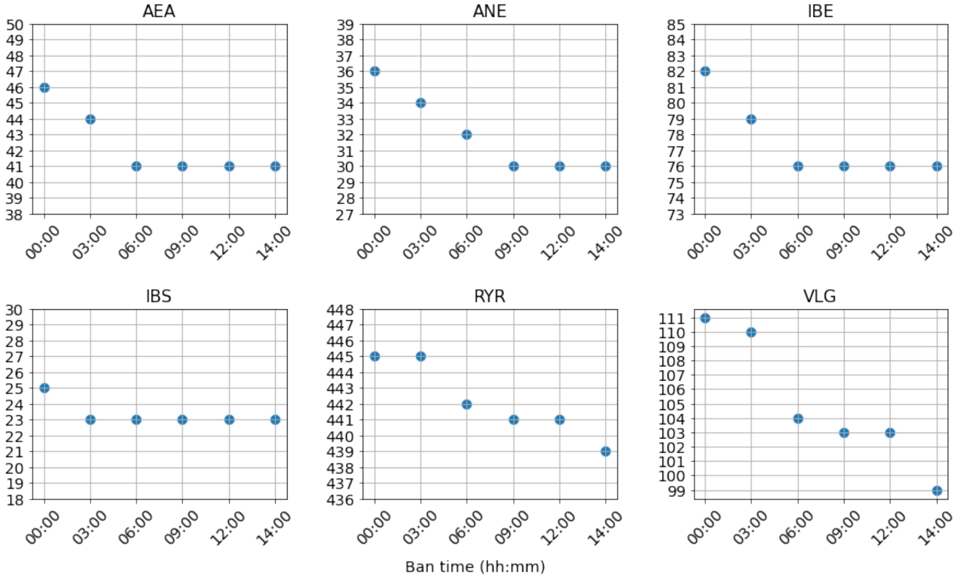


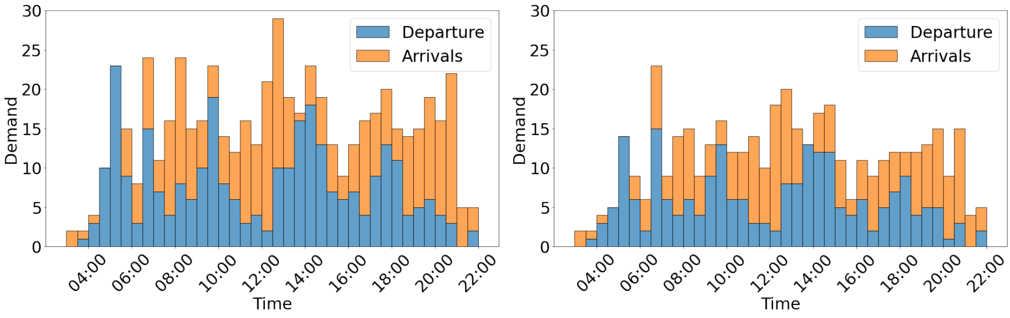
Figure 7. Fleet size variation with ban time.

RYR. However, for small domestic airlines, like ANE or IBS, the potential fleet reduction consists of a significant percentage of their original fleets. IBE is a particular case because the airline manages a large network structured around its hub in LEMD. Therefore, the higher the ban threshold, the more feeder flights are removed, resulting in a subsequently smaller fleet.

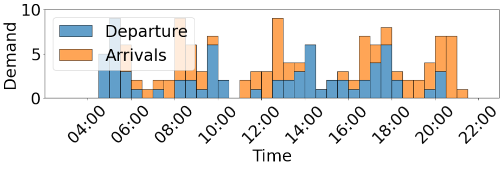
3.4 Infrastructure usage

Ease of capacity issues at airport infrastructure could be expected due to the traffic reduction. Using the demand (looking at SOBT and SIBT) of the airlines considered in this study, Figure 8 presents the histogram of demand for LEMD (the busiest airport) for the 3rd of May 2023. The demand for a 15-h ban (minimum number of flights) is also depicted. As shown in Figure 8c, peaks of reduction of 10 flights in 30 minutes are observed.

Finally, one must consider that the rail network needs to accommodate the seats removed from the



(a) No ban **(b)** 15-h ban



(c) Difference no ban - 15h ban

Figure 8. LEMD demand (SOBT,SIBT) as a function of ban for 3MAY23.

flights. As a function of the ban, this can represent up to 26,700 seats. Due to the frequency and capacity of rail services, the number of seats moved by the rail layer is rather large, with a daily maximum of 123,000 seats for all considered routes, estimated considering the rail services and fleet characteristics [14]. Therefore, the seats transferred from air to rail represent around 22% of the rail capacity for the 15-h ban and, for instance, 14% for a 3-h ban. This means that, on average, for the latter case, if the load factor of the rail is less than 86%, there should be enough capacity to accommodate the required transfer. This average value will differ for particular origin-destination pairs where capacity might be lower than the required demand, *e.g.,* LEMD-LEBL route, particularly during peak hours. The extensive use of multimodality could also modify the flow of passengers at rail stations and their arrival patterns at the airports. This shift in demand could significantly impact the usage of the infrastructure and should be further analysed by including detailed modelling of the demand. However, it is worth noticing that in this work, the supply of rail is not modified as only rail services already planned by Renfe are considered. Therefore, we don't expect a change in rail infrastructure demand.

3.5 Environmental impact

Figure 9 shows the evolution of the daily average of CO_2 emissions of flights operating within Peninsular Spain, emissions corresponding to rail replacement and CO_2 emissions saved as a function of the ban threshold used to replace flights. Recall that to compute the saving of CO_2 emissions fairly, we have considered eliminating air CO_2 emissions but substituting them with the (lower) rail usage ones considering the seats transferred to rail. A ban of 3 hours, for which flight and rail door-to-door times are competitive, already leads to a 22% emission reduction, while a 6-hour ban would reduce the intra-Peninsular Spain emissions by 41%. A longer ban would only slightly reduce emissions while generating a much longer trip time when switching to rail.

3.6 Potential passengers itineraries

With the methodology previously described, not only individual flights and rail services are computed, but possible passenger itineraries, too. These consider potential flight-to-flight connectivity

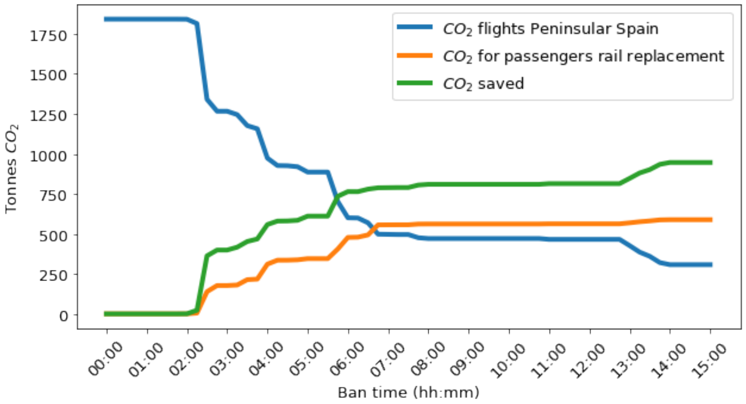


Figure 9. Daily average emissions shifted from air to rail as a function of temporal air-rail ban.

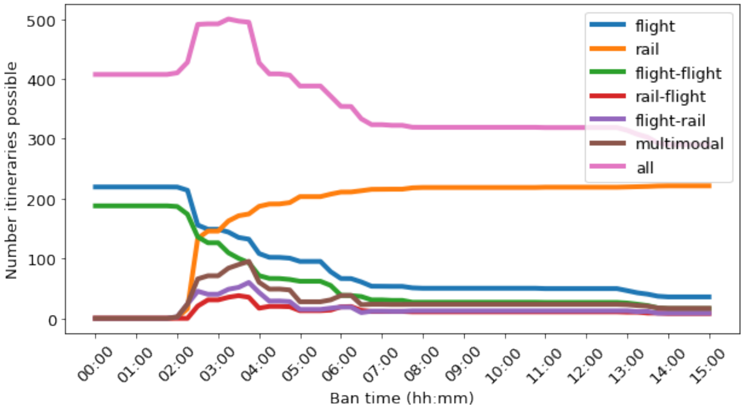


Figure 10. Average number of possible itineraries within Peninsular Spain.

and multimodal journeys (rail to flight and flight to rail).

As Figure 10 shows, as the ban threshold increases, the number of possible air (flight and flight-flight) passenger itineraries decreases while the number of direct rail alternatives increases significantly. This is due to the high frequency of rail services. The number of multimodal itineraries first increases, up to the 3h45 ban, peaking at 95 alternatives, but then decreases as the connectivity is lost due to the lack of consideration of rail-rail itineraries in this study. It is worth noticing how there are more possible multimodal itineraries composed of a flight followed up by a rail segment (maximum of 60) than the other way around (maximum of 38). Surprisingly, the multimodality increases the number of alternatives for passengers from 407, when only flights are considered, to a maximum of 500, obtained with a ban of 3h15. From that moment, the total number of alternatives gets reduced to a minimum of 290.

Focusing on the travel time of the different alternatives as a function of the ban threshold, one can observe how these times increase as the ban is extended (see Figure 11). This is particularly relevant for the multimodal itineraries as the rail segments are longer as the ban increases. Even if the ban is increased significantly, the average rail trip (see rail itinerary) time remains below 3h20 due to the number of services of shorter routes. If the total journey duration (door-to-door) is considered, these types of itineraries could be competitive due to the reduced time of access to train stations

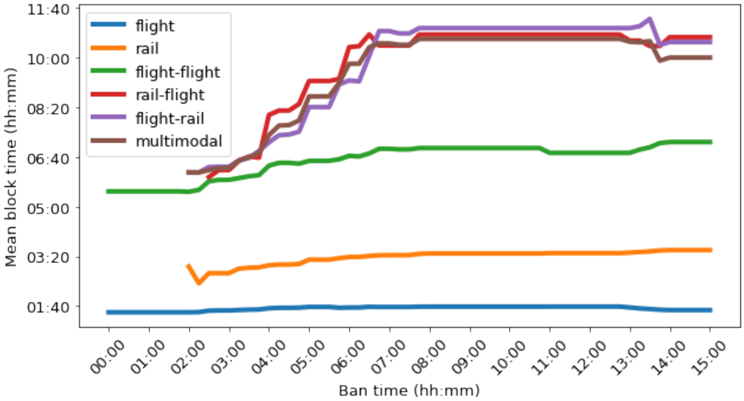


Figure 11. Mean time of possible itineraries within Peninsular Spain

and pre-boarding processing time required, when compared to airports [1]. In Peninsular Spain, the multimodal itineraries on average range from 6h40 to slightly over 10h; this is in comparison with average flight-flight connections, which, without a ban, are 5h30 minutes. One of the main reasons for this is the connecting time between air and rail, which increases, reaching over four hours for a 5-h ban. Further research should consider the willingness of passengers to select these alternatives and the potential impact on demand, which could shift to other alternatives instead.

4. Conclusions and further work

The impact of limiting short flights because there is a train alternative of less than a specific travel time (in-vehicle) is high in terms of number of unique origin-destination routes (from 89 to 55 in the week analysed if a 6-h ban is considered), significant in terms of CO_2 emissions (- 41%) and considerable when we consider the number of seats that should be moved to the train (up to 26,700 seats), but nothing that a service designed for large flows cannot accommodate. The modelling focuses on showing the effect of such bans on the airline's network and not on assessing the rail capacity to absorb the modal shift. Further developments on modelling demand and level of service are a good line of work for the future if appropriate data could be incorporated.

When the airline operates only (or primarily) in the short haul and domestic market (*i.e.,* ANE, IBS), banning flights has serious consequences. When airline planners decide the number of aircraft, their bases, and padding strategies to cover a specific set of pairs, they fix the main percentage of operating costs[22]. The measure could mean a fleet reduction of up to 20% for local airlines with a primarily domestic network. This would entail strategic decisions at the company level, as the network is a strategic element of competitiveness. However, pan-European airlines with highly diversified networks, like RYR, suffer less from the measure if it is not implemented at the European level. In the case of airlines operating a hub, such as IBE, their short-haul business segment will be impacted, but not their long-haul business segment (in terms of the fleet). The measure could be an opportunity to assign assets to more profitable business segments if multimodal connections are designed carefully, as the level of service for connecting passengers is critical, which is also considered for future work.

The work focused on the supply and computation of possible passenger itineraries given a flight ban policy. The analysis should be extended to include demand aspects of travel, considering seasonal patterns on demand and travel time preferences. In particular, with a focus on modelling the perception of time based on elements of the journey (in mode vs. waiting times) and passenger characteristics. This should be the subject of future research.

Merging OpenSky's data with the data of railway operators allowed us to develop a complete bimodal network model, to understand the principles of airline network design and to analyse the potential contributions of railways in the middle distance market, considering a new scenario of multimodal transport and zero-emissions commitment.

OpenSky is the first open database that provides enough flight and aircraft information to perform network, schedule and resource analysis, which is of great value to science and academia. This work has some areas for future development related to the airline network design and resource allocation problems. For those, it is necessary to have accurate information related to the airports where the airline operates (algorithms to deduce missing airports), to know the airline's overnight and maintenance bases, to reconcile icao24's transponder ids with aircraft type, and to add information related to actual and scheduled flight times. Eliminating sources of error in this information is vital to accurately determining rotations and adjusting network and fleet assignment models.

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Open data statement

Section 2 and Table 1 describe the data used for this article. All datasets are open and available. The datasets used to produce the results of this article can be accessed from [12] in https://doi.org/10.5281/zenodo.10642324.

Reproducibility statement

Section 2 describes in detail the methodology used to compute the results presented in this article. The code has been developed in Python and R, and it is accessible in https://github.com/UoW-ATM/joas_air_rail_network_analysis.

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