Transportation Research Part D 138 (2025) 104513

Contents lists available at ScienceDirect

Transportation Research Part D

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

Can rail reduce British aviation emissions?

Malcolm Morgan [a,*], Zia Wadud [a], Sally Cairns [b,1]

[a] Institute for Transport Studies, University of Leeds, Leeds, United Kingdom
[b] Sally Cairns & Associates Ltd, United Kingdom

ARTICLE INFO

Keywords:
Aviation
Emissions
High-speed rail
UK
Origin-destination

ABSTRACT

We analyse UK airport origin–destination data from 1990 to 2021 to understand the extent to which a modal shift to rail may reduce aviation emissions. We find that 41 % of UK aviation passengers travel on routes that can be done by rail in less than 24 h. However, these passengers account for only 14 % of UK aviation emissions because long-haul flights contribute the majority of emissions. Some popular destinations (e.g. Spanish Islands) are inaccessible by rail and may be suitable for destination switching. We also find rapid growth in flights to international hub airports used for connecting journeys. This has implications for carbon accounting, suggesting that a significant and growing proportion of UK residents' aviation emissions are being excluded from national accounts. Finally, the paper recommends some interventions that might encourage a modal shift to rail.

1. Introduction

The United Kingdom is one of the largest international aviation markets in the world (Dyson and Sutherland, 2021). This represents a significant source of climate impact, which is often excluded from domestic carbon budgets and planning. However, international aviation emissions will be included in the UK's 6th carbon budget (which will operate from 2033), and tackling them is critical to meaningfully address the UK's contribution to climate change. The vast majority (over 80 %) of passengers on international flights to or from the UK are leisure travellers (CAA, 2019). While many in the aviation industry and the Government's own Jet Zero strategy argue that ongoing aviation growth is possible (DfT, 2022). Others, including the Government's own advisory body, the Climate Change Committee, argue that technological solutions are unlikely to be sufficient, and a significant reduction in the total number of flights is required (CCC, 2021).

So, is the British holiday abroad doomed? Perhaps not. For, while the British fly internationally a lot, many flights are relatively short, with over half of all passengers going to the five closest European countries (Eccles, 2022), as holiday travellers tend to favour the convenience of the sub-3-hour flight (Cass, 2021). The distances involved for many trips are within the plausible operating range of rail. Therefore, this paper explores the theoretical potential for modal shift between flying and rail to decarbonise the UK's international travel. It takes a geospatial approach to consider the scale of aviation passenger journeys that might have a viable rail alternative, and the likely impacts on emissions if such a switch took place.

Specifically, this paper attempts to answer the following research questions:

* Corresponding author.
E-mail addresses: m.morgan1@leeds.ac.uk (M. Morgan), Z.Wadud@leeds.ac.uk (Z. Wadud), sally@scairnsa.co.uk (S. Cairns).
[1] Independent researcher.

https://doi.org/10.1016/j.trd.2024.104513
Received 18 July 2023; Received in revised form 1 October 2024; Accepted 11 November 2024
Available online 29 November 2024

1. Between which airports do travellers currently fly? What is the distribution of passengers, flights, passenger kilometres, and total emissions?
2. What proportion of UK domestic and international aviation emissions are caused by routes that have a possible rail alternative now or in the future, and what would be the emissions implications of modal shift occurring?

As such, the paper does not consider relative pricing, or customer preferences for 'fastest route possible' – it primarily aims to focus on whether journeys actually have a viable rail alternative and what the emissions impact of a switch would be, whilst the discussion section then takes a somewhat broader perspective about the mechanisms needed to achieve modal shift.

The central questions are timely for several reasons. First, the massive disruption caused to the aviation sector by COVID-19 means that there is an opportunity to plan for major changes in transport behaviour. For example, the French Government required Air France not to compete with domestic rail as a condition of its €7 billion bailout (Briginshaw, 2020), and has since banned domestic flights between cities where there is a rail alternative of less than 2.5 h, as part of its 2021 Climate Law (Limb, 2021). A significant modal shift might occur if this principle were adopted for international flights (Dobruszkes et al., 2014; Givoni et al., 2012; Karpman, 2022). Second, the European Union is prioritising a Trans Europe Network (TEN) of high-speed rail (European Commission, 2023; Ros, 2023). Thus, the European rail network's speed and connectivity should improve over time. This will make rail an increasingly attractive alternative to flights. Finally, as other sectors of the economy decarbonise, the rising emissions from aviation will become increasingly hard to ignore. Policymakers will probably find it easier to address aviation demand, if they can promote modal shift from short-haul flights to rail. If this is the case, understanding where alternatives exist, and the potential contribution to emission reductions of encouraging such switching is essential.

2. Literature Review

While aviation emissions contribute a small overall percentage of greenhouse gas emissions (IEA, 2022), they are gaining increased attention for several reasons. First, there is growing evidence that, in addition to their contribution to CO_2 emissions, planes also contribute to climate change in a range of other ways (European Commission, 2020; Jungbluth and Meili, 2019; Lee et al., 2021). Second, flying is recognised as the most polluting form of transport in terms of emissions per passenger kilometre (BEIS, 2022a), and so there are calls to promote a modal shift to less polluting modes (Nelldal and Andersson, 2012). Third, demand for aviation has been growing rapidly (Gössling and Humpe, 2020) and outstripped improvements in aircraft fuel efficiency, meaning that, aviation emissions are growing in both absolute and relative terms (Teter and Kim, 2022). Finally, the literature on climate justice focuses on the fact that flying is a luxury undertaken by a small minority of people (Cass, 2022). This pattern is observable internationally, with most flights occurring in wealthy countries (Aamaas and Peters, 2017), and even within nations. For example, in the United Kingdom, 76 % of flights are taken by only 20 % of households (Büchs and Mattioli, 2021).

The UK has been a leader in the international aviation sector throughout its history. Significant technological innovations have emerged from the UK, such as the invention of the jet engine (Wittle, 1930), and several major aviation companies, such as Airbus and Rolls Royce, operate within the UK. The UK also has strong international links through the legacy of its empire, its role as a maritime trading nation, and its roles in international organisations such as the United Nations. Finally, the UK's location on the western edge of Europe has made it a prominent hub for *trans*-Atlantic flights. London Heathrow has long been one of the busiest airports in Europe, and the UK has fourteen airports in Europe's top 100, which is more than any other country.

The UK was tightly integrated into the European aviation sector through its membership in the European Union and with the US sector via the US-EU open skies agreement (European Parliament, 2007). However, these relationships have weakened after Brexit (GSA, 2021). There has been an average passenger growth rate of around 5 % per year between the early 1970s and the pandemic, albeit with some variability caused by economic changes (Cairns et al., 2006). The aviation sector underwent deregulation in the 1990s, leading to the rise of low-cost airlines (Diaconu, 2012). Falling ticket prices have largely resulted in wealthier households flying more rather than an increase in flying by poorer households, with around half of UK households taking no flights in any given year (Büchs and Mattioli, 2021; DfT, 2017).

Despite the growing research interest in flying, the available data remains limited. Many papers rely on surveys, such as the International Passenger Survey, to measure travel behaviour, while papers focussed on emissions often use data on the consumption of fuel as a measure of aviation demand. Fewer papers have investigated the types of origin–destination data which is common when studying land transport (Grimme and Maertens, 2019). This is surprising as the commercial aviation industry is dominated by a comparably small number of companies operating publicly timetabled services. Indeed, websites allow real-time tracking of aircraft across the globe (Flightradar24, 2022) and could be a future way to track flights and emissions (Klenner et al., 2022; Quadros et al., 2022) but not passenger flows. However, little research has been done on aviation origin–destination data because it is commercially valuable and expensive to acquire outside the US (Park and O'Kelly, 2016; Puliafito, 2023). Some authors have used ABS-D data (Klenner et al., 2022) or airport statistics (Puliafito, 2023). For example, Avogadro et al. and Reiter et al both used the commercial Official Airline Guide (OAG) database (Avogadro et al., 2021; Reiter et al., 2022). This paper builds on that work, but with a somewhat different focus – namely, all air trips with an origin or destination in the UK; use of a more detailed dataset; and use of a relatively broad definition of 'viable rail alternative' (as described in the methodology).

2.1. Rail in the UK and Europe

In the age of steam, the UK often operated the fastest railways in the world, such as London and North Eastern Railway's (LNER)

Mallard, which set and retains the world speed record for a steam locomotive in 1938 at 203 km/h (National Railway Museum, 2023). However, the UK was slow to adopt the newer technologies being embraced in places such as Japan and France. Today, the UK has an extensive but only partially electrified rail network, often limited to speeds less than 201 km/h. The opening of the Channel Tunnel Rail Link (rebranded HS1) between 2003 and 2007 links London to the European rail network. Construction has begun on HS2, a new line from London to Birmingham (HS2, 2023; NAO, 2020).

High-speed and long-distance rail options beyond the Channel Tunnel are significantly more advanced. Several European countries, including France, Spain, Italy, and Germany, have constructed lines with speeds between 250 and 320 km/h (see Fig. 1). Many European countries are expanding or upgrading their domestic rail networks through the European Union's Trans-European Network (TEN) programme, linking their high-speed rail networks together.

From the UK perspective, the most significant link is the Eurostar service that provides direct rail routes from London to Paris, Brussels, and Amsterdam. The Eurostar is often used as an example of successfully achieving a modal shift from flying to rail, as it now has about 80 % of the London to Paris market share (Doomernik, 2016). Paris is the hub of the French rail network and provides onward connections to Germany, Switzerland, Italy and Spain.

Research on the modal shift between air and rail typically focus on routes between 300–700 km and regards trips longer than 1000 km as being uncompetitive (Zhang et al., 2019) (e.g. London to Marseille or Prague) as long as High-Speed Rail (HSR) exists. However, most HSR journeys are less than three hours, implying shorter trips (e.g. London to Paris). Several studies examining the potential for emissions reductions from a modal shift of short domestic flights find evidence of significant reductions (Avogadro et al., 2021; Baumeister and Leung, 2021; Rajendran and Popfinger, 2022; Reiter et al., 2022). For example, Avogadro et al. explore opportunities for air-to-rail modal shift for air trips in Europe of up to 800 km, and identify that 7.2 % of intra-European flights might be amenable to modal shift (on the basis of an increase of up to 20 % in the weighted passenger travel time being acceptable), whilst Reiter at al (2022) suggest domestic aviation emission reductions of 2.7 to 22 % are possible from air to rail switching within Germany, depending on the scale of modal shift presumed to take place. Other papers have found that HSR can increase emissions by providing better airport connectivity and thus increasing travel demand (Gu and Wan, 2022). There is also evidence that competition from HSR results in airlines reducing fares (Bergantino et al., 2015), which may lead to increased demand for flying. All the research listed above considers modal shift within the current socio-economic framework, where the choice between train and plane is seen as an individualistic decision based on factors such as price and journey time. Yet policies such as the French ban on domestic flights show that more radical collective action is possible. This paper therefore explores the possibilities of modal shift from flying to rail to seek an understanding of how far rail can help solve the intractable problem of aviation emissions.

3. Methods and data

To understand the current and historical demand for aviation, we sought to construct an airport-to-airport origin–destination matrix of the UK's domestic and international flights. The UK's Civil Aviation Authority (CAA) publishes detailed data on international passengers between airports (CAA, 2022a). The CAA also published similar data on flight punctuality between major UK airports and their destinations, which provides a count of total flights on most routes (CAA, 2022b).[2] A range of manual and automated data processing techniques was employed to clean the data and link together data from different sources and years. Then the data was geocoded to turn airport names into latitude/longitude coordinates, thus enabling the measurement of route distances.

Ultimately, cleaning these datasets into a consistent origin–destination dataset of domestic and international flights to/from the UK was possible. This includes the correct locations of the airports, the number of passengers per year, and, when available, the number of flights. Data was collected for each year from 1990 to 2021. However, between 1997 and 2000, the CAA did not publish data on domestic flights, so this data is missing from our results.

In total, 1.4 % of origin–destination pairs could not be matched to a suitable pair of airports, representing 0.00004 % of passenger flows in 2019. Most of these are caused by the CAA data including an "other airport" category for most countries. These are likely small private aircraft flying to small airports and are unlikely to affect the overall results significantly.

3.1. *Flight distance and passenger kilometres*

Once the origins and destinations were calculated, the distances between airports were computed based on the great circle distances. In practice, this will be a slight underestimate as planes rarely fly the perfect route, instead having to navigate around airspace restrictions. To account for these detours, we increase the length of the journey based on the great circle distance. Detour factors of 14.3 % (flights < 1000 km), 7.3 % (1000 – 4000 km) and 4.8 % (>4000 km) were used based on existing literature (Dobruszkes and Peeters, 2019).[3] These distances were multiplied by the number of passengers to give annual passenger kilometres between each airport pair. Note that this calculation is standardised over all routes and years, so does not account for local effects, such as airspace

[2] Similar data exits for other European Countries on Eurostat, but it is not as spatiotemporally extensive https://ec.europa.eu/eurostat/databrowser/explore/all/transp?lang=en&subtheme=avia.avia_pa.avia_par&display=list&sort=category&extractionId=AVIA_PAR_UK.

[3] Note that in the official UK statistics BEIS use a flat 8% detour factor for all distance bands (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/https://doi.org/1083857/2022-ghg-cf-methodology-paper.pdf). The average detour factor used in this paper varies slightly from year to year due to the varying mix of long and short routes, but was 7.0% in 2021 and 6.5% for 1990–2021.

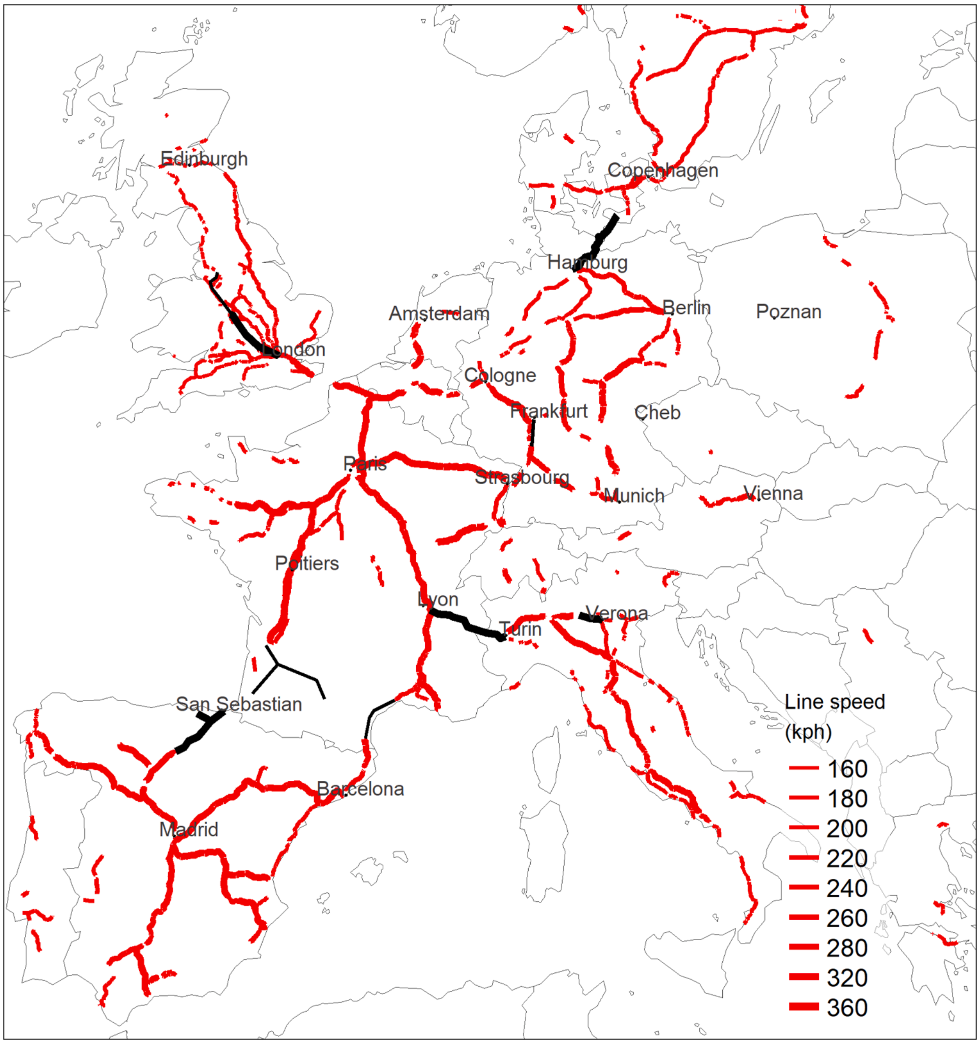

Fig. 1. Map of the European high-speed rail network from OpenStreetMap (Geofabrik, 2021). Operating lines in red with selected under-construction lines (thick black) and proposed lines (thin black). Place names highlight important connecting locations for *trans*-European rail travel. Lines shown are limited to those of 160kph and above, to avoid overwhelming the map, although many countries, such as Germany, may have lines which are nearly as fast operating across a richer network. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

closures during wars that may cause significant detours at certain times.

3.2. Emissions factors

To account for the improving fuel efficiency of aircraft between 1990 and 2021 and the different fuel burn rates of domestic, short-haul, and long-haul flights, we used the annual BEIS emissions factors for business flights (BEIS, 2022a). These factors provide average emissions per passenger kilometre and include the impacts of radiative forcing and the emissions associated with getting the fuel from the oil well to the tank (WTT). Unfortunately, BEIS has only been providing these emissions factors since 2012, so for the period 1990 to 2012, we used Larsson's estimates of average global aviation emissions per passenger kilometre (Larsson et al., 2018). As Fig. 2 shows, Larsson's estimates overlap in time with the BEIS estimates, showing that they most closely match BEIS's short-haul emission figures. This is unsurprising, as the short-haul band would cover all flights between European countries and most domestic flights in China and the USA. These markets collectively represent the bulk of the aviation sector (World Bank, 2020), so the global average would be expected to approximate the short-haul average. Larson's estimates do not appear to include WTT emissions and are slightly less than the BEIS emission factors. We used the Larsson results to extrapolate historical emission factors for each year and distance band, with the results shown in Fig. 2.

Finally, the appropriate emissions factor is applied to each flight's passenger kilometres to estimate the total annual emissions.

3.3. Defining areas reachable by rail

To identify flights with a rail alternative, it is necessary to define how far people may reasonably travel by train, both now and in the future. For example, rail is traditionally considered competitive with flying on routes of less than 700–1000 km (Börjesson, 2014; Givoni, 2006; Jansson and Nelldall, 2010). Using this definition would include unlikely cross-sea routes from London to Dublin (460 km). Furthermore, it would exclude longer but currently achievable journeys by rail, such as London to Rome (1,400 km), which may become more attractive due to rail improvements and policies to discourage aviation.

To define a plausible rail study area, we combined published 5-hour travel time isochrones (Tran Dinh, 2022) for rail travel across Europe from 21 other key locations (shown in Fig. 3). These 5-hour isochrones were combined to estimate travel time from London. For example, Frankfurt is four hours from Paris, and Paris is two hours from London, so an estimate of 7 h (4 + 2 + a 1-hour connection) is produced, which is similar to the actual travel time of 6 h 28 min. The isochrones were then cross-checked against the rail travel website "the man in seat 61" (https://www.seat61.com) to ensure plausible routes had been considered. The intention was to define an area that reflects the near future of the European rail network, of places that would be reachable in a day. While all the destinations considered are reachable by rail today, some currently require an overnight stop due to the specifics of the current timetable. Fig. 3 shows the extent of the rail study area, coloured by rail travel time from London St Pancras station. The stations used to produce the isochrones are labelled on the map. As the travel times were generated by combining isochrones, the travel times from London are representative rather than an accurate reflection of current long-distance travel. For example, the map generally assumes that travellers do not have significant waiting time when making onward connections for each five-hour stage, and does not make allowance for faster routes/services that take more than five hours. Fig. 3 also shows the extent of the European rail network, with red lines showing the existing network and black lines highlighting selected lines proposed (thin) or under construction (thick) in black.

3.4. Rail emissions

While rail emissions per passenger km are typically much lower than flying, they are not zero and so must be accounted for. This is a complex task due to the significant variations in trains, routes, and electricity grids across Europe, making a comprehensive analysis beyond the scope of this paper. Thus, a simplification has been made by estimating the $kgCO_2$ per passenger km for each section of the European rail network. For non-electrified lines 0.036 $kgCO_2$/pass-km is assumed which is comparable to the average diesel train in the UK (ORR, 2021). For electrified lines a variable rate has been used based on the average carbon intensity of each country's electricity grid (EEA, 2024) and an assumed energy consumption of 0.08 kWh/pass-km (Andersson and Lukaszewicz, 2006). Note that energy consumption per pass-km is very sensitive to the load factor of the train and so ranges from 0.07 to 0.18 kWh/pass-km (Andersson and Lukaszewicz, 2006). The choice of 0.08 kWh/pass-km reflects the observed average for modern electric trains. Thus, assumed emissions for electric trains range from 0.00064 $kgCO_2$/pass-km in Sweden to 0.05544 $kgCO_2$/pass-km in Estonia.

Unlike planes, whose routes approximate to a straight line (see above), trains may have to take significant detours along the rail network. Consider a trip from Edinburgh to Copenhagen, which is a short flight due East. But by train requires a lengthy trip via London, and Brussels. A simple shortest path analysis was performed on the European rail network to estimate the equivalent rail distance for each flight, accounting for the maximum line speeds. While this does not account for timetabled services, it captures the non-uniform travel distance increase implied by switching from air to rail. Each section of track was given a $kgCO_2$ weighing value based on its length, whether it is electrified (as recorded in the OpenStreetMap), and the carbon intensity of the electricity grid in the relevant country (EEA, 2024). These weighting factors were summed to provide an overall $kgCO_2$/pass-km for each route.

4. Results

Fig. 4 shows the distribution of passengers, passenger kilometres, and emissions to all airports with direct UK flights in 2019, based on the CAA data. Unsurprisingly, passenger kilometres and emissions are closely linked. We present data from 2019, as it is the most recent pre-Covid year, and more representative of long-term trends than 2021 data. It is clear that the vast majority of passengers are travelling to/from Europe, with a smaller cluster of demand in the United States, the Middle East, and South-East Asia. However, this data does not include the final destination of passengers, just the destination of the plane departing/arriving in the UK. Therefore, it is likely that hub airports such as New York, Dubai, and Hong Kong are over-represented, as onward connections by passengers are not recorded. This is particularly noticeable for Australia and New Zealand, which are popular destinations for UK travellers, but have few direct flights due to their distance from the UK.

Fig. 5 further illustrates the imbalance between passenger numbers and emissions by showing the distribution of passengers (left), passenger kilometres (middle), and emissions (right). Data for countries in the top 10 for either passengers or passenger kilometres are shown individually, while all other countries' data is grouped into regions.

Fig. 5 shows that while around three-quarters of passengers travel domestically or short-haul to Europe and thus may have an alternative to flying, these account for only about a third of passenger kilometres and less than a third of the UK's aviation emissions. Conversely, this means that a relatively small proportion of passengers are responsible for the majority of kilometres travelled and emissions.

Fig. 6 shows the distributions over time, with the significant drop in flying due to the pandemic clearly visible. A smaller passenger drop also followed the 2007/08 economic crisis, with passengers and passenger kilometres not exceeding pre-crisis levels until 2014. Due to improvements in fuel efficiency, emissions have not returned to their 2007 peak. However, emissions have been rising since 2014 and would probably have exceeded the 2007 peak if the pandemic had not caused a drastic reduction in flights. The inclusion of

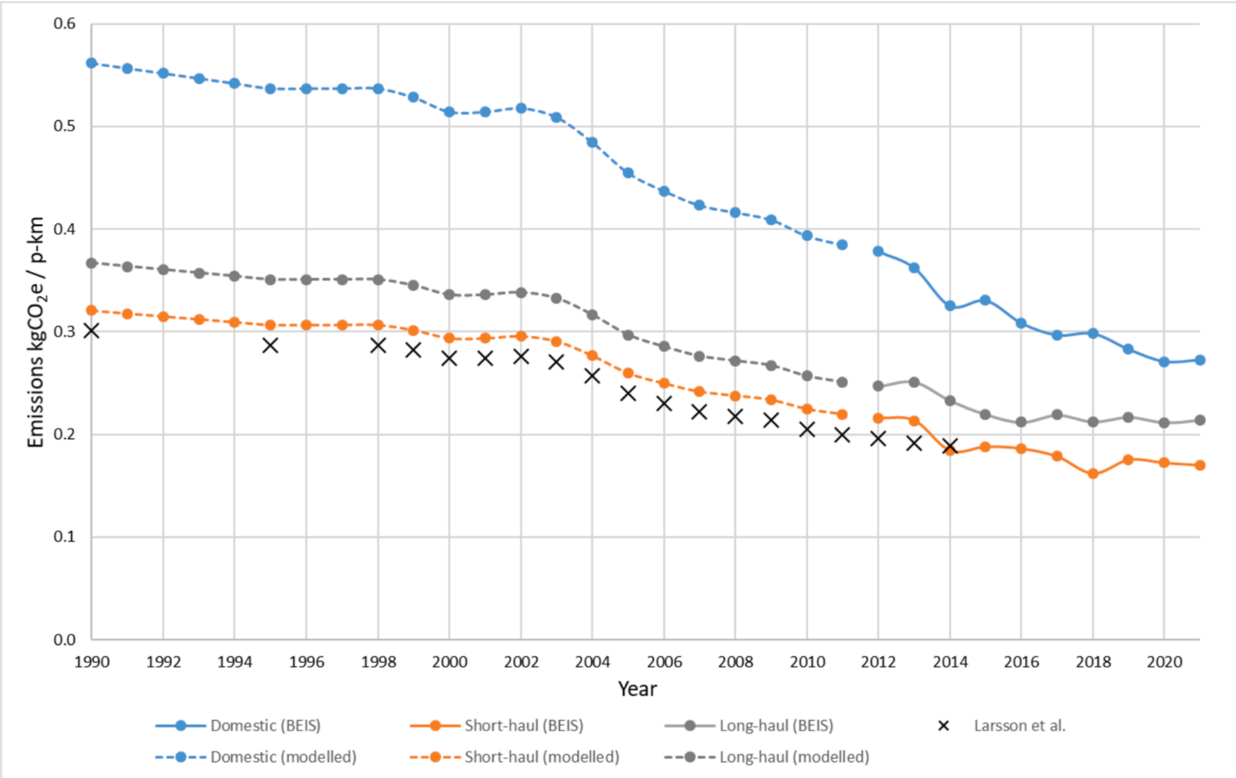

Fig. 2. Assumed emissions factors for domestic, short-haul (<3,700 km), and long-haul (>3,700 km) flights kg of CO_2 equivalent (GWP100).

data for connecting flights might also show a less positive picture for emissions.

4.1. Popular short and medium-haul routes

The previous section highlighted that most passengers were flying to the nearest European countries. As the data enables a route-level analysis, it is possible to identify and map popular routes. Fig. 7 shows the passenger distribution in 2019 and highlights that many of the most popular routes, such as London to Edinburgh, have a viable alternative to flying. However, the geography of the British Isles also results in many frequently travelled routes that lack easy alternatives to flying, such as London to Belfast, Dublin, and Jersey, all of which require sea crossings by ferries. The map also highlights the significant proportion of flights going to popular tourist destinations such as the Spanish Islands.

Fig. 7 also highlights several important patterns in domestic aviation demand. First, as an archipelago of inhabited islands, Britain has a long tail of short-distance low-demand routes such as the 396 people who flew the 19 km from Coll to Tiree (in the Hebrides) in 2019. Fig. 7 excludes the 6,598 routes (80 %) with less than 10,000 passengers per year which comprise 1.1 % of total passengers in 2019. The small scale of these flights makes their total emissions insignificant compared to the rest of the UK's aviation sector, and they are also likely to be relatively amenable to electrification. An extreme example of these short but hard-to-replace flights is the Channel Islands, with 1.6 million passengers flying between the Channel Islands and the rest of the British Isles in 2019, an average of 9.2 flights per resident on the islands. Given that Guernsey and Jersey have less than 700,000 tourists per year (ITV, 2020; Visit Jersey, 2023), this is an exceptionally high flying rate compared to the UK average (4.4 flights per person).

The second part of the tail of the low-volume routes is private flights. Although the CAA passenger data does not distinguish between scheduled and chartered flights, the many routes that carry a tiny number of passengers suggest that these represent private flights. For example, seven passengers flew the 60 km between Sheffield and Leeds. Although they do not account for a large share of emissions, private flights are considered a particular environmental concern, given that they typically have higher emissions than scheduled services due to less efficient passenger loadings, and there is a social equity issue, given that they are almost exclusively undertaken by relatively wealthy people and organisations (Beevor and Murray, 2019).

Flights to the UK's offshore oil rigs also contribute to a sizable number of domestic flights. The CAA data does not distinguish between different oilrigs, and so we represent all oilrigs as a single point in the North Sea. It should be noted that these flights are treated like other domestic flights in calculating emissions. However, they are taken by helicopter and are likely to consume more fuel per passenger kilometre than fixed-wing aircraft.

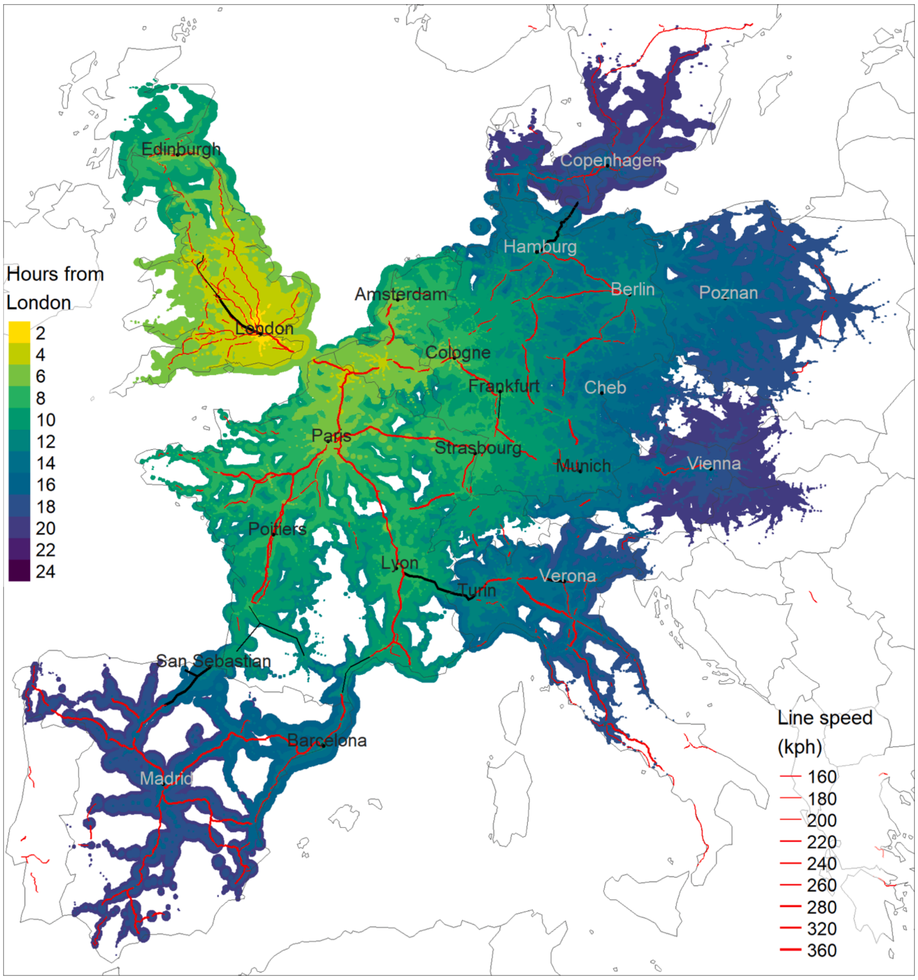

Fig. 3. Approximate train travel isochrones from London St Pancras station used to define the study area. Existing high-speed rail lines are shown in red. Selected lines under construction (thick) or proposed (thin) are shown in black. Actual analysis is focused on all air travel between the UK and Europe, and does not merely consider London. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

4.2. Travel patterns over time

It has been well-documented that the number of aviation passengers has been growing rapidly for decades. However, this growth has not been uniform across all routes. Some routes, such as London Heathrow to Dubai, have grown from obscurity to become one of the most popular routes in the UK, while others, like London to Tokyo, are declining.

Individual routes can be misleading over thirty years as demand can switch between airports serving the same destinations. This is especially true of London, which has six international airports. For example, passengers on the London Heathrow to Paris Charles De Gaulle route have been declining in recent years while passengers between London Gatwick and Paris Charles De Gaulle have been increasing. To compensate for these patterns, the airports were clustered into groups, comprising all airports within 90 km of each other. The 90 km threshold was chosen so that all of London's airports would be in the same cluster. This clustering then enabled the creation of Fig. 8.

Fig. 8 shows the most popular routes from UK to other cities, based on the cities that have been within the ten most popular routes for at least one year. In practice, this means that all routes involved London. Notably, several routes with rail alternatives, such as Paris, Brussels, Glasgow, and Manchester/Liverpool, were in decline pre-Covid. However, other short-haul destinations such as Edinburgh, Dublin, and Amsterdam/Rotterdam are growing. Amsterdam, Dublin, and Istanbul are popular hub airports for long-haul flights, and some of the growth may be due to people making onward connections rather than increasing demand to visit these destinations. However other hub airports (Paris, Frankfurt) have not seen a growth in demand. There was a notable inflexion point for several European hub airports in 2010, which may be due to the UK's main hub airport (Heathrow) being at capacity after 2009 (Hoon, 2009). However, this also coincides with a general recovery in aviation after the 2007/8 economic crisis.

Dublin's recent rapid growth may be linked to its introduction of pre-clearance of US immigration in 2011 (CAPA, 2016). If this is

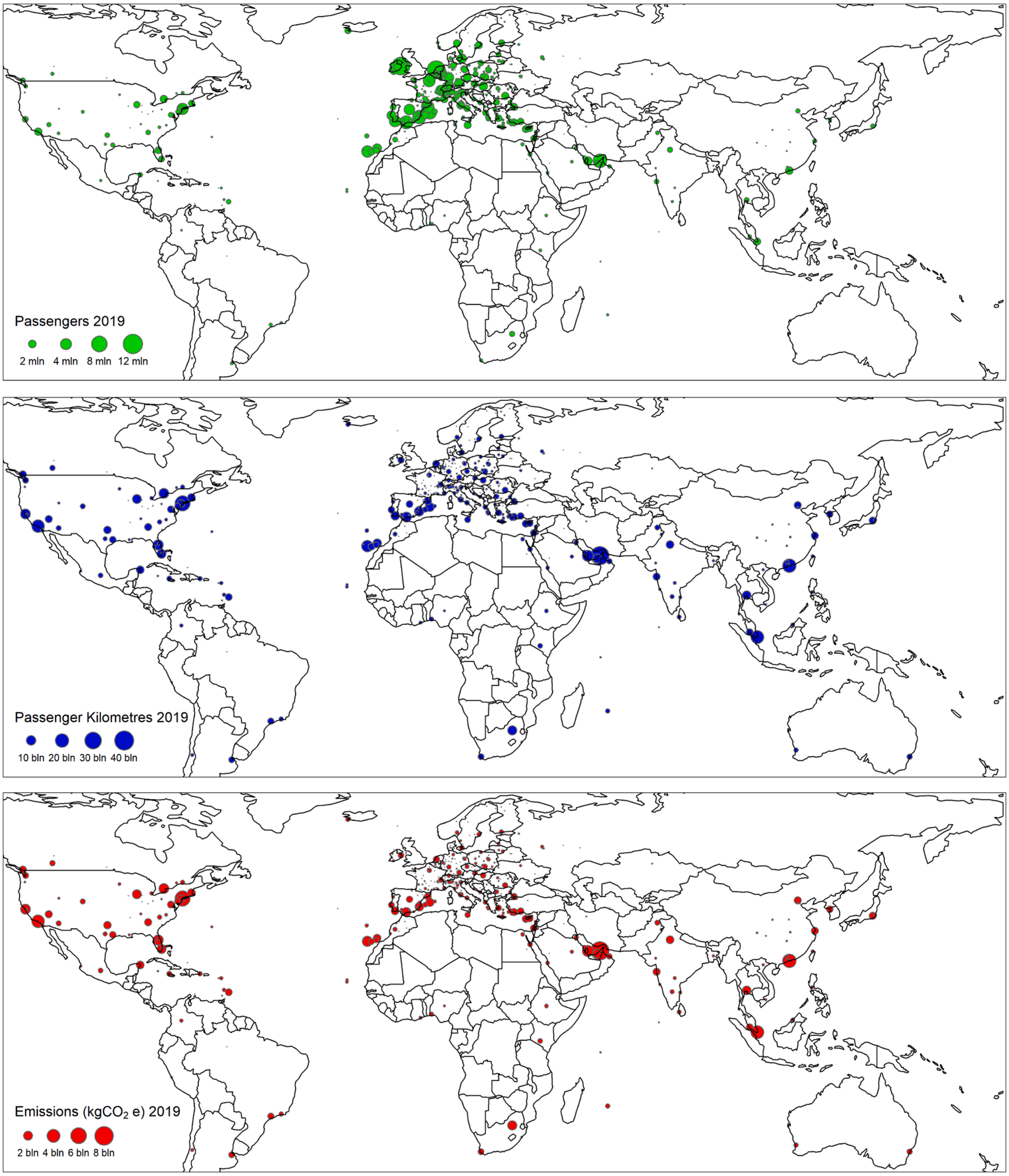

Fig. 4. Map of the distribution of international passengers (top), passenger kilometres (middle), and emissions (bottom) for direct flights starting/finishing in the UK in 2019. For clarity, UK airports have been removed. No adjustments for connecting flights have been made.

the case, it highlights the risk of under-estimating British aviation emissions by only looking at direct flights, an approach which has often been adopted when assessing the UK's international aviation emissions (Büchs and Mattioli, 2021; DfT, 2017). In practice, this can mean that emissions from a long-haul flight are split into a short-haul flight attributed to the UK and a long-haul flight attributed to another country. Even more concerning is the rapid growth in passengers to hubs such as Dubai and Istanbul, which are used for onward flights to India, East Asia, and Oceania.

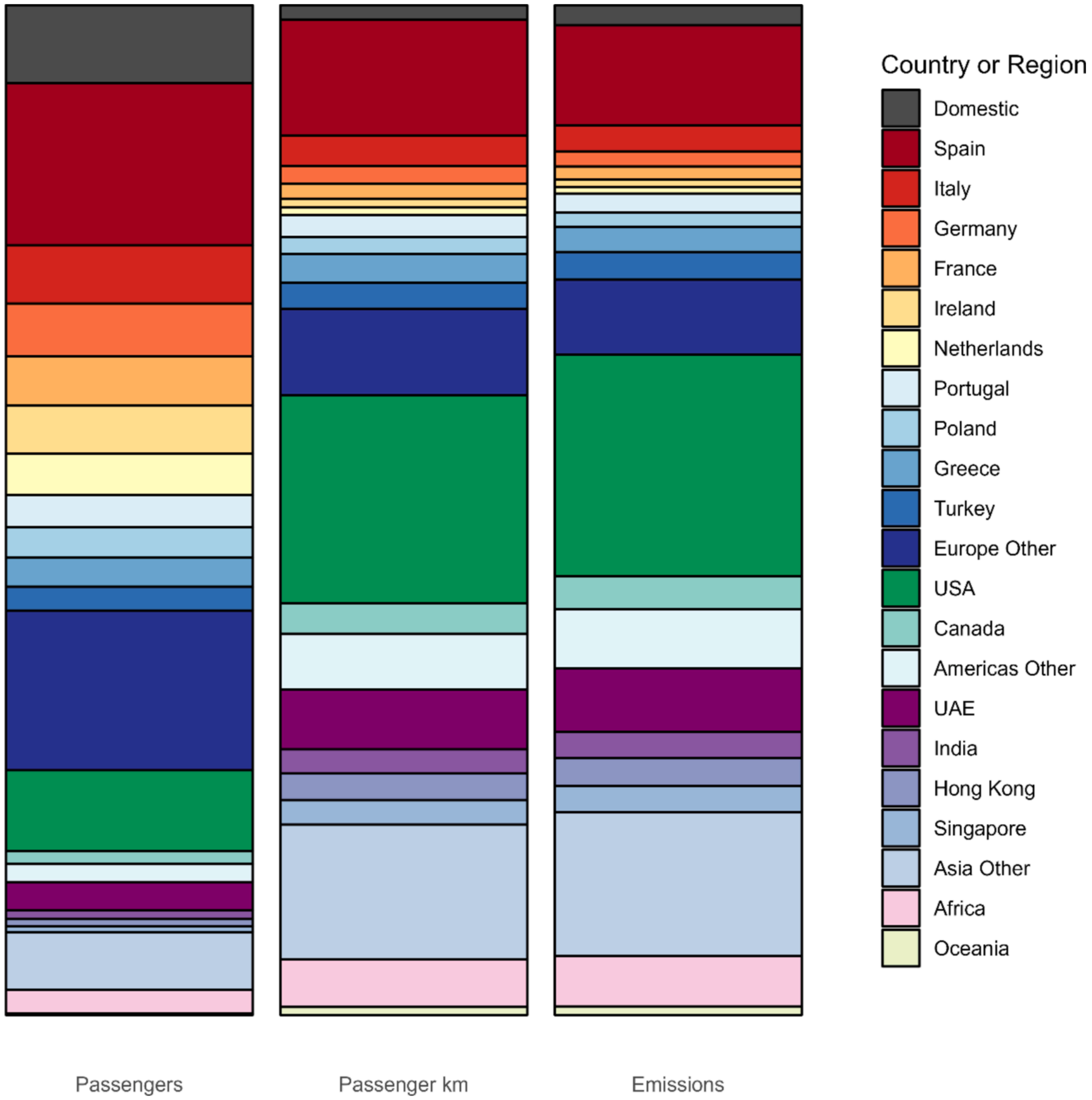

Fig. 5. Distribution of passengers, passenger kilometres, and emissions for direct flights between selected countries and regions and the UK in 2019. The green blocks for the USA also mark the division between Europe and the rest of the world, highlighting the importance of domestic and European travel in terms of the size of passenger flows (only). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

4.3. Comparing patterns of aviation with rail options

Fig. 9 shows the number of passengers from the UK flying to different European airports, with colour coding depending on whether they are within the rail study area described earlier. Table 1 then provides summary statistics for each European country, breaking down the data depending on whether the airport falls within or outside the rail study. In summary, it shows that 41 % of flights are being made within the rail study area, but they only account for 14 % of emissions. Should this shift occur, although there would be additional emissions from rail, our initial estimates suggest that these would be equivalent to only 9.9 % of the emissions from the current flights.

Fig. 10 shows the routes used to calculate rail emissions. It is worth noting that the analysis tended to favour routes to Italy via Switzerland, but in practice routes via the South of France can be easier due to fewer connections. The under-construction Turin-Lyon high speed rail line will strongly favour a route via the south of France from the mid-2030 s and significantly cut rail journey times between the UK and Italy.

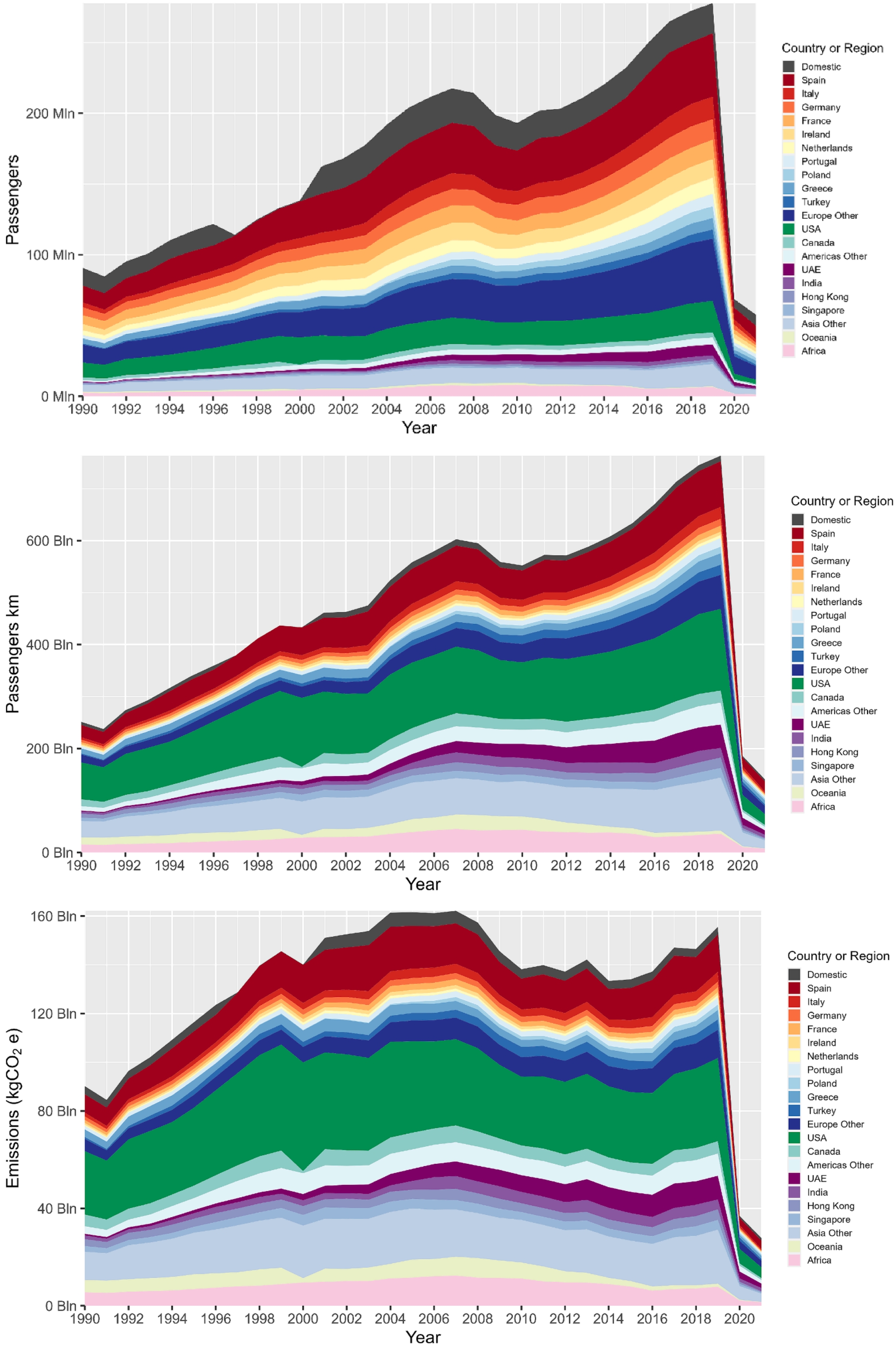

Fig. 6. Passengers (top) passenger kilometres (middle) and emissions (bottom) per year from 1990 to 2021, based on direct UK flights. They are coloured by destination country or region. Note that domestic flight data is missing between 1997 and 2000.

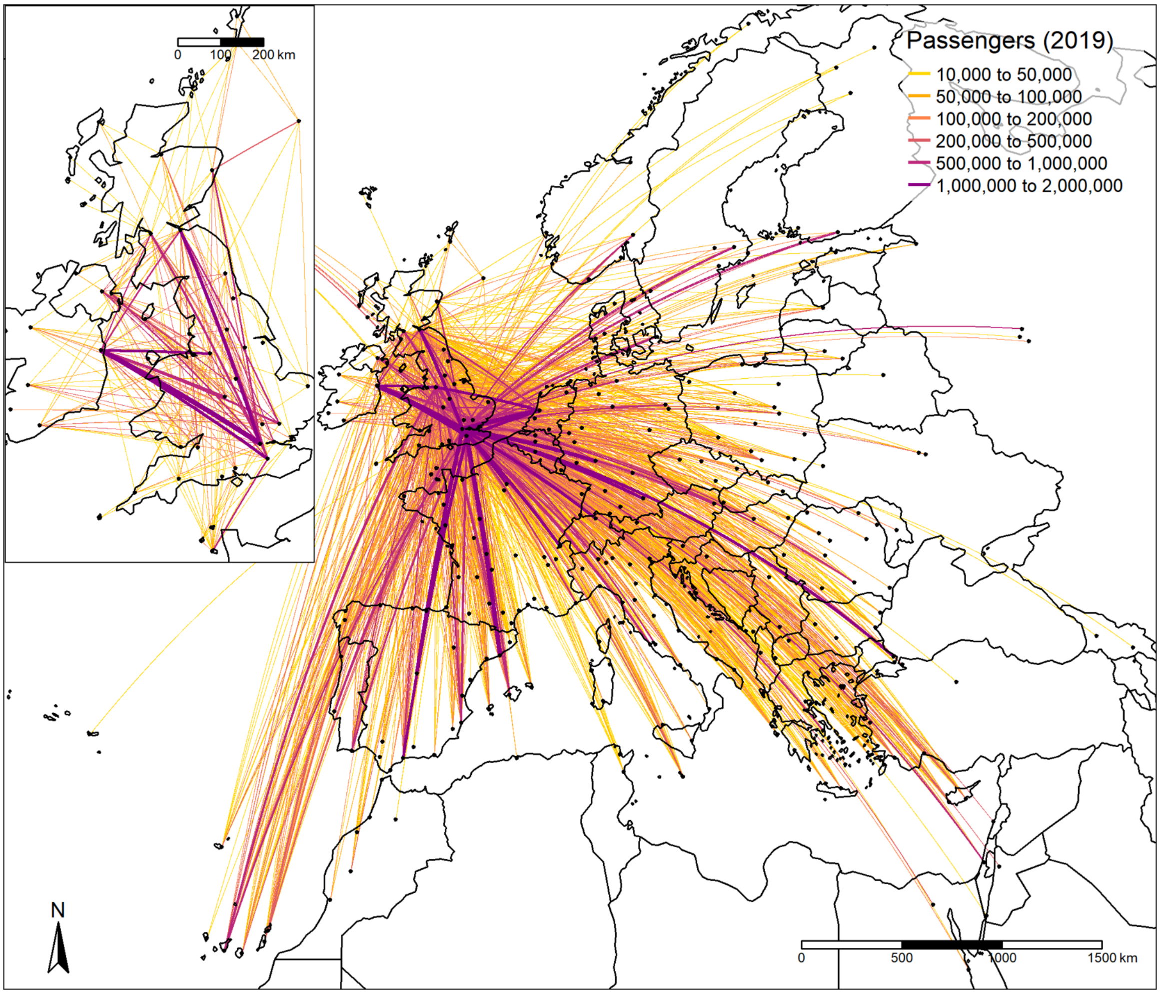

Fig. 7. Routes from/to UK airports of less than 4,000 km, coloured by the number of passengers in 2019. Routes with less than 10,000 passengers per year have been removed for clarity. Inset shows a zoomed-in map of flights within the British Isles.

5. Discussion

This paper has shown that a long-time series origin–destination dataset of UK aviation can reveal interesting patterns and trends in flight demand. As a significant proportion of the global aviation sector, this dataset also sheds some light on global travel patterns. This more spatially detailed dataset complements existing research on the trends in UK aviation, particularly the overall trend of rapid demand growth outstripping fuel efficiency improvements (Teter and Kim, 2022). Greater detail nuances the narrative by highlighting the importance of comparatively few routes. This is especially important when considering decarbonisation, as it helps focus the debate. However, the data suggest that while flights to Spain are a significant proportion of trips, many are comparatively less important from an emissions perspective as they are short-haul (Dobruszkes et al., 2022). Conversely, the rapid growth in flights to Dubai, which has already overtaken popular destinations such as Barcelona and Rome in terms of passengers per year, is far more concerning, given that it will comprise long-haul high-emissions flights, particularly when it is part of a connecting journey.

Identifying key routes also contributes to discussions around modal shift, particularly the opportunities for a shift to rail. The EU has long-term ambitions to promote an integrated European high-speed rail network (European Commission, 2023), which could in principle, include the UK. As it is already possible to travel from London to Paris (2 h 15 min), Brussels (1 h 48 min), and Amsterdam (4 h 07 min) by high-speed rail, other popular destinations could be connected to London. In particular, Barcelona, Cologne, Geneva/Zurich, Frankfurt, and Milan/Rome would be worth further investigation, either by high-speed rail or sleeper trains. While such routes may only account for a small proportion of aviation emissions, they account for a sizable proportion of trips and may shift public attitudes about flying. This would be especially true if combined with policies to encourage destination switching, such as replacing a flight to the Canary Isles with a train to Barcelona. If many holidaymakers shift their short-haul flights to rail, it may become easier to question the social acceptability of long-haul flights, thus enabling more significant emissions savings.

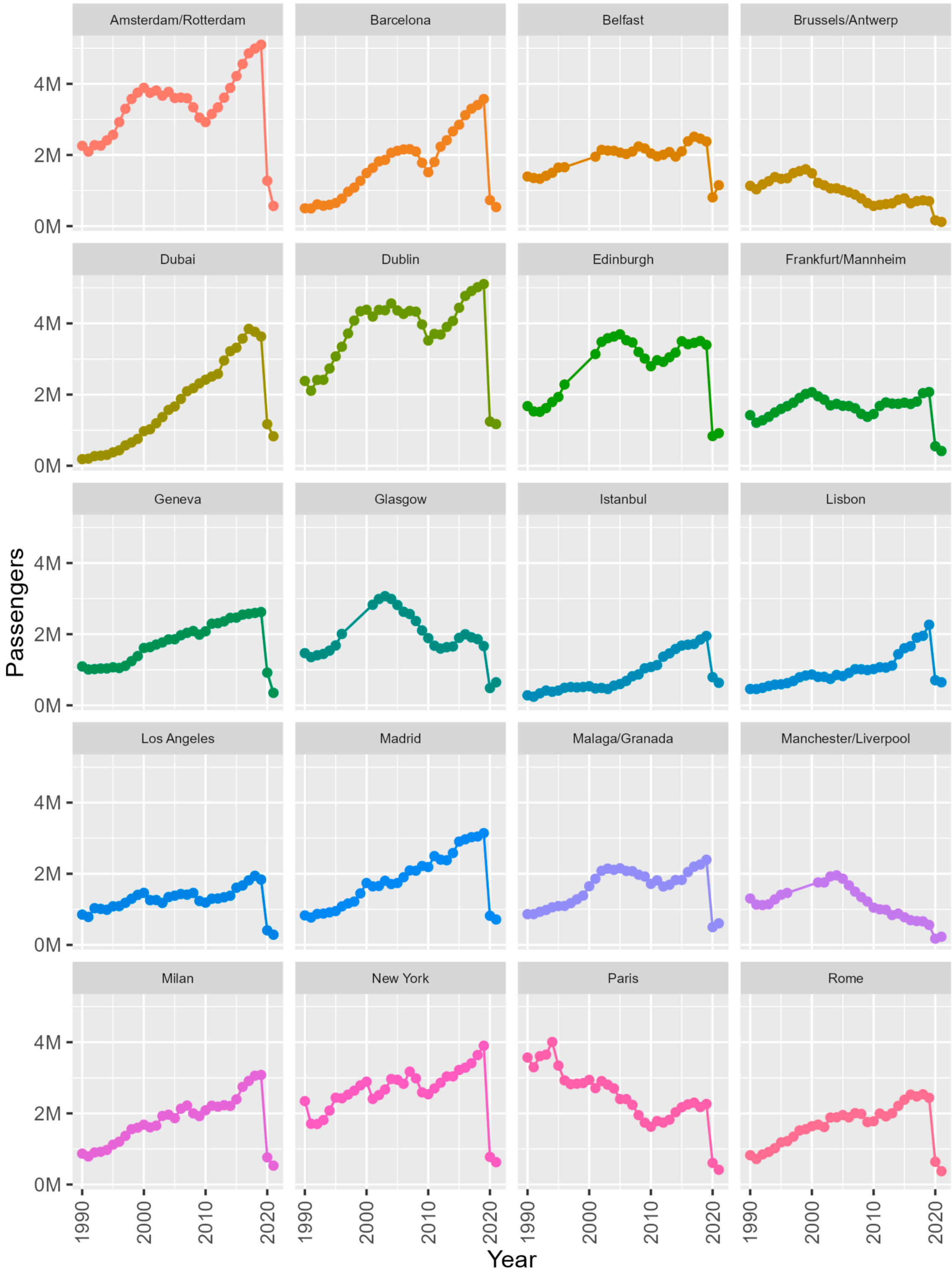

Fig. 8. Passengers per year on the top routes (domestic or international) between London airports and other cities. Cities with multiple airports have been clustered together. All of these routes have been within the top 10 for at least one year between 1990 and 2021. Note that domestic route data is missing between 1997 and 2000.

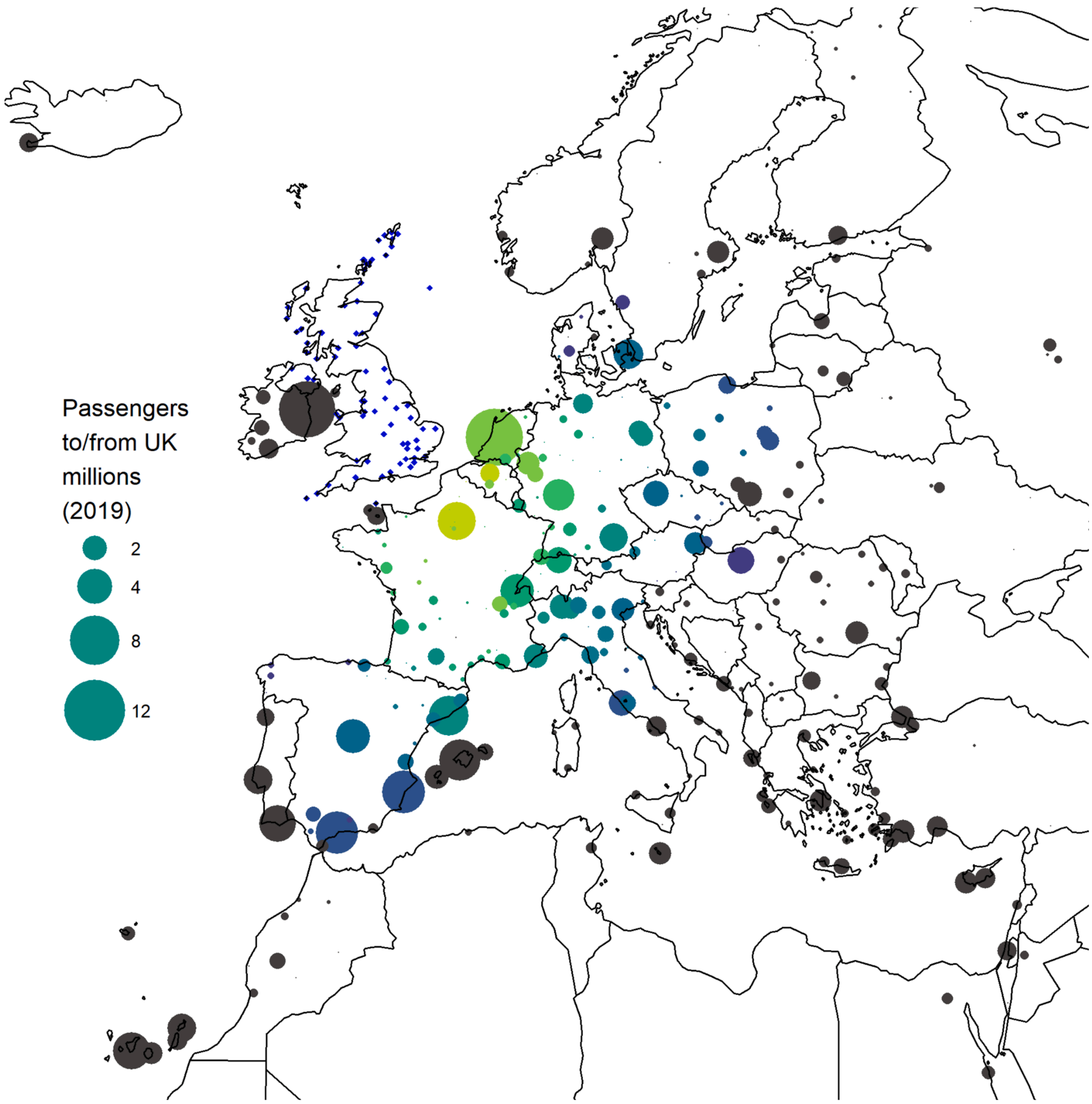

Fig. 9. Number of 2019 passengers flying to European airports from the UK. Colours match the rail travel time isochrones in Fig. 2, with airports outside the rail study area shown in grey. British airports are marked with a blue diamond. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

5.1. Comparison with official statistics

The latest official Government estimate of the UK's international aviation emissions was published in 2022 (BEIS, 2022b). While the broad trends in emissions are the same, the total emissions are significantly lower. The Government estimates the peak emissions in 2007 to be less than 40 $MtCO_2e$ compared to over 160 $MtCO_2e$ in our estimates. Such a significant difference (4x) is worth exploring in depth. The first reason for the significant difference is that the UK Government only considers domestic, and international flights ***departing*** the UK to contribute to the UK's carbon footprint (DfT, 2017), which is consistent with the UNFCCC framework. In contrast, we have included all flights in and out of the UK. Thus, our estimate is immediately doubled. Around two-thirds of passengers on flights to and from the UK are residents of the UK (CAA, 2019). Thus, the UK arguably should receive a greater share of the responsibility for the emissions. The share of UK residents on flights will vary by route, and it is likely that some planes, such as charter flights to Spain, are flown almost exclusively by British tourists.

Conversely, Heathrow's role as a major hub airport means that many long-haul flights may have a high proportion of non-UK residents. Ideally, data on the nationality of passengers would be used for route-level analysis. This would be a productive area of research to further investigate issues of climate justice raised by flying.

Table 1
Summary of the passengers, passenger kilometres, and flight emissions from flights to/from UK airports in 2019. Note this does not include onward connections. The final column estimates the emissions if these journeys had been done by rail rather than flying. Rail emissions are only estimated within the study area.

	Passengers (thousands)		Passenger km (millions)		Flight Emissions ($MtCO_2e$)		Rail Emissions ($MtCO_2$)
Within the rail study area	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**
Spain	24,897 (9 %)	19,737 (7.1 %)	39,593 (5.2 %)	48,178 (6.3 %)	6.95 (4.5 %)	8.46 (5.4 %)	0.587
Germany	14,480 (5.2 %)	54 (0 %)	13,161 (1.7 %)	66 (0 %)	2.31 (1.5 %)	0.01 (0 %)	0.278
France	13,333 (4.8 %)	258 (0.1 %)	11,225 (1.5 %)	304 (0 %)	1.97 (1.3 %)	0.05 (0 %)	0.127
Italy	12,917 (4.7 %)	3136 (1.1 %)	17,037 (2.2 %)	5867 (0.8 %)	2.99 (1.9 %)	1.03 (0.7 %)	0.254
United Kingdom	11,807 (4.3 %)	9523 (3.4 %)	6885 (0.9 %)	3869 (0.5 %)	1.95 (1.3 %)	1.09 (0.7 %)	0.13
Netherlands	11,128 (4 %)	186 (0.1 %)	5711 (0.7 %)	162 (0 %)	1 (0.6 %)	0.03 (0 %)	0.126
Switzerland	5883 (2.1 %)	26 (0 %)	5468 (0.7 %)	33 (0 %)	0.96 (0.6 %)	0.01 (0 %)	0.054
Poland	4985 (1.8 %)	3318 (1.2 %)	7241 (0.9 %)	5375 (0.7 %)	1.27 (0.8 %)	0.94 (0.6 %)	0.25
Denmark	3447 (1.2 %)	120 (0 %)	3712 (0.5 %)	117 (0 %)	0.65 (0.4 %)	0.02 (0 %)	0.111
Hungary	2404 (0.9 %)	189 (0.1 %)	3950 (0.5 %)	338 (0 %)	0.69 (0.4 %)	0.06 (0 %)	0.082
Austria	2394 (0.9 %)	14 (0 %)	3167 (0.4 %)	22 (0 %)	0.56 (0.4 %)	0 (0 %)	0.068
Czech Republic	2345 (0.8 %)	13 (0 %)	2788 (0.4 %)	20 (0 %)	0.49 (0.3 %)	0 (0 %)	0.088
Belgium	1559 (0.6 %)	0 (0 %)	871 (0.1 %)	0 (0 %)	0.15 (0.1 %)	0 (0 %)	0.012
Sweden	643 (0.2 %)	2049 (0.7 %)	728 (0.1 %)	3157 (0.4 %)	0.13 (0.1 %)	0.55 (0.4 %)	0.021
Luxembourg	591 (0.2 %)	1 (0 %)	361 (0 %)	0 (0 %)	0.06 (0 %)	0 (0 %)	0.004
Slovakia	500 (0.2 %)	233 (0.1 %)	735 (0.1 %)	387 (0.1 %)	0.13 (0.1 %)	0.07 (0 %)	0.016
Ireland		13,213 (4.8 %)		6455 (0.8 %)		1.13 (0.7 %)	
Portugal		8902 (3.2 %)		16,678 (2.2 %)		2.93 (1.9 %)	
Greece		8103 (2.9 %)		21,941 (2.9 %)		3.85 (2.5 %)	
Europe		21,540 (7.8 %)		39,540 (5.2 %)		7.01 (4.5 %)	
World		8103 (2.9 %)		488,438 (64 %)		106.01 (68.1 %)	
Total	113,312 (40.8 %)	164,461 (59.2 %)	122,631 (16.1 %)	640,947 (83.9 %)	22.28 (14.3 %)	133.28 (85.7 %)	2.209

The UK Government accounts for international aviation based on refuelling from bunkers (DECC, 2019), leading to two minor discrepancies with our estimates. First, the Well to Tank (WTT) emissions included in our calculations are accounted for elsewhere in the UK's carbon accounts. WTT emissions add around 0.022 $kgCO_2e$ per passenger km (11 %). Second, as the UK emissions are based on volumes of fuel sold in the UK, they do not account for fuel purchased outside the UK. Airlines may be tankering some fuel into the UK to exploit relative differences in fuel prices between the UK and other countries (Eurocontrol, 2019).

However, these differences are small. The other major reason for difference between our estimates and Government figures is that they do not make any allowance for the CO_2e effects of non-CO_2 emissions. Our methodology uses the BEIS recommendation, which involves using a multiplier of 1.9 – i.e. it nearly doubles the aviation impacts. This is consistent with the GWP_{100} central estimate in the European Assessment of Transport Impacts on Climate Change and Ozone Depletion (Sausen et al., 2005).

Therefore, the differences between the estimates occur due to subjective choices on how to attribute emissions, and whether to include the non-CO_2 effects of aviation. While the UK government will likely retain its methodology for consistency and compatibility with international reporting, the method underplays the true harms of flying and the benefits of reducing flight passenger kilometres.

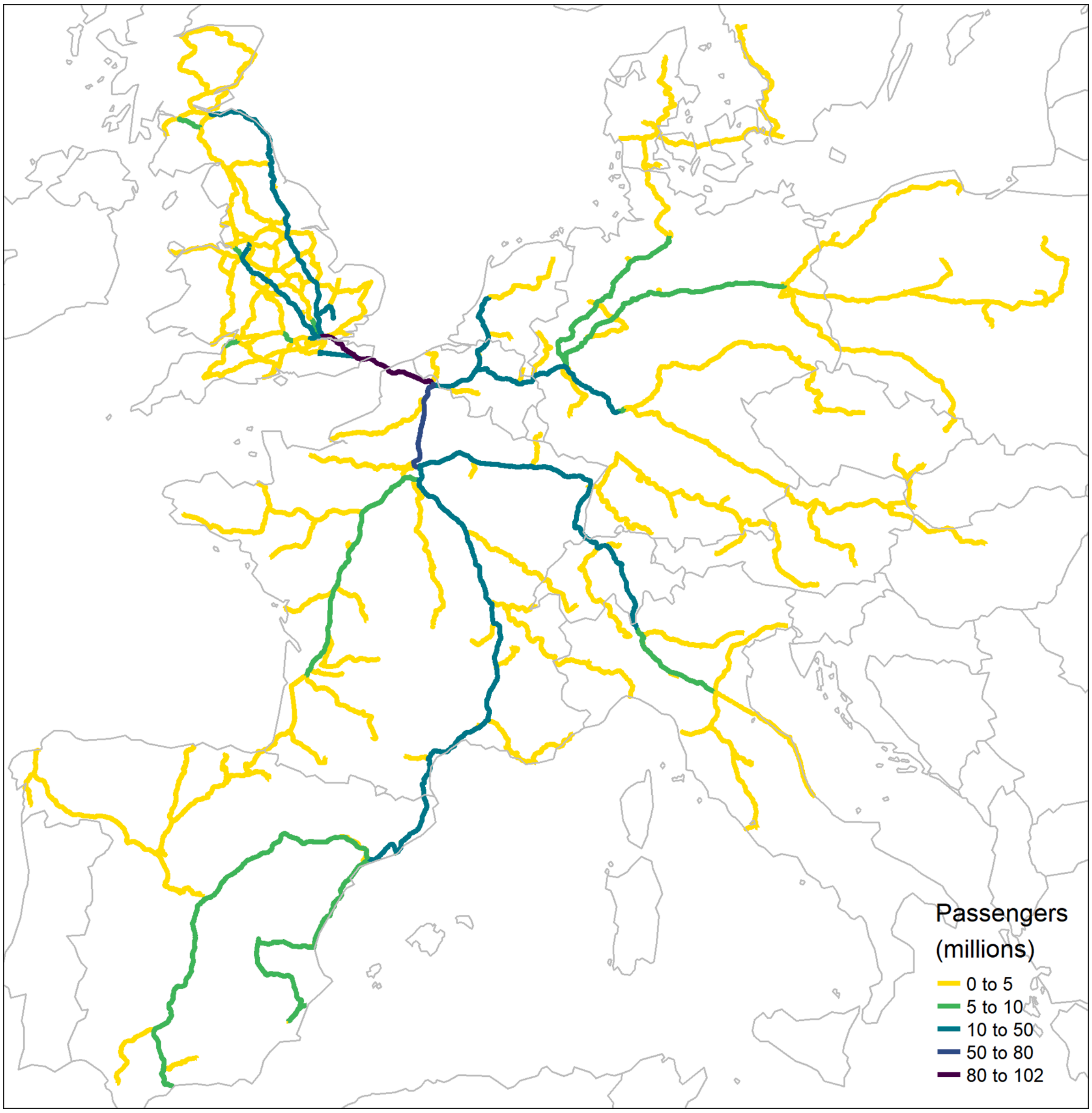

Fig. 10. Illustrative rail routes between airports in the study area. Lines are coloured by the number of annual passengers in 2019 if all passengers travel by rail instead of flying. This is intended to highlight the relative importance of comparatively few lines for enabling international rail travel.

5.2. Possibility of significant modal shift to rail

This paper has explored the potential of rail to contribute to a modal shift away from flying. Given that, compared to the train, the plane is often faster and cheaper on most routes it is unlikely that a modal shift will occur without significant policy intervention. More taxation of flying and investment in rail are often suggested as generic solutions to promote a modal shift. These are critical issues, but better covered elsewhere. Instead, here we explore some specific changes relevant to UK-Europe travel.

5.2.1. Reducing journey times with more direct services

Unlike airlines, which can offer many direct services, most train journeys between Britain and the continent require multiple connections. Connections increase journey times and the complexity of travel, exposing travellers to the risk of missed connections. All of these make rail a less attractive option for international travel.

More direct services to key destinations could help reduce the complexity and risks related to rail travel and reduce journey times. For example, as Eurostar is compatible with the British and French systems, services could be extended to connect places with existing direct services to London or Paris, providing routes such as Birmingham to Barcelona or Manchester to Munich. Routes such as these could significantly cut total journey times with limited changes to the existing network. For instance, the High Speed 1 line from London to the Channel Tunnel comes within 600 m of the High Speed 2 line from London to Birmingham and linking these lines would enable through services to operate.

While there are technical challenges to overcome in linking different main lines, which often have different signalling and electrification systems, these are not insurmountable, especially in the medium to long term. Before the construction of HS1, Eurostar services operated a bi-mode system using 25 kV AC overhead wires in France and switched to 750 V DC third rail electrification in England. In contrast, HS1, HS2, and the French network are all designed to the same standards, and thus should be compatible with all existing and future Eurostar trains.

A more significant barrier to more integrated routes is the UK Government's requirement that passengers clear passport control before boarding an international train. This prevents train services from serving a mix of national and international passengers, as is common on trains between other European countries. This is a challenge as few rail routes would be viable if they only served the UK – Europe market, but many more would work if intermediate stops were permitted. For example, a Birmingham to Barcelona train might stop in London, Paris, Montpellier, and Girona, thus serving multiple in-demand routes.

A change in UK policy would be required to move passport checks from the station to the train to enable domestic travellers to board and alight the train without a passport while only checking the passports of passengers crossing the Channel. Ideally, passport checks would be conducted while the train was in motion. However, stopping the train to carry out such checks might still be considerably less inconvenient for passengers than requiring them to change trains.

5.2.2. Travel through the Channel Tunnel

The high-speed line between London and Paris opened in 2007, with a low-speed alternative route used between 1994 and 2007. The route is used for domestic and international passengers, freight trains, and the cross-channel shuttle service for road vehicles. Eurostar is the only passenger rail operator on the route and runs about 20 services per day between London – Paris, 13 services between London – Lille/Brussels, and four services between London – Amsterdam in each direction. Eurostar operates several train variants on these routes, but their newest train seats 902 passengers. Thus, Eurostar has a maximum cross-channel capacity of 24 million passengers annually. In practice, they carry about 11 million passengers as each train is not full (Topham, 2023).

In comparison, Fig. 10 identifies 102 million passengers per year that might use the Channel Tunnel, a 4.25-fold increase from current capacity, assuming each train was packed. Eurostar currently operates about 1.9 trains per hour in each direction between 5 am and midnight, but high-speed lines are operated at higher capacities. For example, the French TGV service between Paris and Lyon operates up to 13 trains per hour, and the UK's HS2 line is planned to operate up to 18 trains per hour. To move 102 million passengers per year would require at least seven trains per hour in each direction operating 24 h a day. The LeShuttle and freight trains also use the tunnel, implying an overall average of 14.5 trains per hour. Currently, the tunnel operates a peak rate of 20 trains per hour (Getlink, 2023). So, while a significant shift from planes to trains is not beyond technical feasibility, it is likely that upgrades to the line would be required, and the Channel Tunnel would reach capacity. Still, there is also considerable scope to increase passenger numbers from the current situation before capacity limits are reached.

5.3. Sleeper trains

Sleeper trains are experiencing a revival in Europe (Bearne, 2023) and can make long journeys much more acceptable as time spent both sleeping and travelling is efficient, and travellers arrive at their destination well-rested. Conversely, many short-haul budget flights have early departure times, meaning travellers arrive at their destination tired. For example, the Eurostar overnight ski train to the Alps already has a positive reputation for enabling passengers to do a whole day skiing on arrival. Sleeper trains also push transport demand into the less busy nighttime, reducing the risk of domestic lines becoming congested with international trains (Georgiadis, 2023; Knowles and Farrington, 1998; Rapid Transition Alliance, 2022). Revisiting the knowledge gained as part of the subsequently cancelled Nightstar services might be helpful in establishing costs and feasibility, whilst considering the changed context.

5.4. Package deals and prebooking

Many UK tourists take advantage of package deals combining travel and accommodation. These often include additional benefits such as airport transfers or car rental, and thus are often cheaper and more convenient than booking each individually. The airline industry has actively promoted these package holidays, which are also used to induce demand for aviation. For example, airlines will promote deals when and where they have spare capacity on their planes. While this makes economic sense for the airlines, it draws holidaymakers away from lower-carbon alternatives. There is an opportunity to promote lower carbon holidays by offering comparable train plus hotel packages in the same places where existing package holidays are sold and/or to encourage people to destination switch, thereby reducing both emissions per km, and total distance travelled.

Flights and trains also differ in how much they can be booked ahead of time. In particular, booking a train more than three months ahead is often difficult, whereas flights can be booked much further in advance. Enabling more advanced bookings would better align with the current conventions engendered by air travel. In the UK, there are still improvements to be made even to the booking of linked Eurostar and onward European travel, and Eurostar does not seem to offer last-minute deals on services which are below capacity, which might compete with the kind of last-minute deals available for flights.

5.5. Connections to Ireland

Ireland was excluded from the analysis in this paper as there is no rail link between Great Britain and Ireland. However, it is clear from Fig. 7 that there is significant travel demand between Great Britain, the Republic, and Northern Ireland. These are among the shortest flights, so they are attractive candidates for a modal shift to less carbon-intensive modes. However, the recent public debate on the issue also highlights the potential challenges with building new infrastructure. One option might be a Channel Tunnel style rail link. Although the Irish Sea is much wider than the Channel, travel demand between the UK and the island of Ireland is also greater today than the London-Paris travel demand when the Channel Tunnel opened.

Given that most flights are between London and Dublin, it would make sense to connect Dublin to Great Britain with an onward connection to Belfast rather than the now-abandoned proposal for a link between Northern Ireland and Scotland (Walker, 2021). Short-term solutions could include upgrading the North Wales Coast Line to enable direct trains between London and the ferry port at Holyhead. Alternatively, as electric planes will only be suitable for short-range flights of $<$ 300 km within the foreseeable future and may not be common for decades (Schäfer et al., 2018; Thomas, 2022) they could link Dublin to Birmingham airport, which will be a 37-minute train journey from London on the HS2 line.

6. Conclusions

6.1. Limitations and further work

This study has not made a direct comparison of travel times and costs as in most cases the train is slower and more expensive than the plane. Thus, this study is an exploration of possibilities rather than a prediction of routes likely to experience modal shift. Nevertheless, an exploration of costs and travel times would likely allow a more in depth understanding of route and mode choice.

As discussed above the exclusion of onwards connections means that this study may significantly underestimate the long-haul emissions of UK passengers. Further analysis particularly of major hub airports could provide estimates for how many UK passengers make onward journeys and where they go.

6.2. Conclusions

In this paper, we have quantified the number of passengers, passenger kilometres, and emissions from the UK aviation sector over the last three decades, and looked at the potential for rail to substitute for aviation. Five key results have emerged from the analysis.

First, 41 % of all passengers passing through UK airports could have a rail alternative, although in most cases, the current rail alternative is slower and more expensive. As the rail network in Britain and Europe is expected to improve, especially regarding international rail links, there is an opportunity to promote modal shift from planes to trains for a sizable share of passengers. Fig. 10 highlights that a small number of rail corridors could serve the majority of UK-Europe demand, and so this work highlights where to focus further research.

Second, the 41 % of passengers that might be shifted to rail only account for 14 % of aviation emissions. The vast majority of emissions are associated with long-haul flights beyond the practical range of rail networks. On the other hand, the passengers that could be shifted accounted for approximately 22 $MtCO_2e$ in 2019. While rail journeys are not yet emissions free the much lower per-km emissions rate resulted in an average emissions saving of 90 % even when accounting for the longer trip distances required by some rail routes. However, our method used simplified emissions rate for rail journeys, and did not account for the variety of load factors across Europe. Nor does it factor in the embodied emissions of constructing rail infrastructure (Miyoshi and Givoni, 2013; Olugbenga et al., 2019) or their non-CO_2 effects.

Third, destination switching could boost the potential for emissions savings. For example, 5.4 % of all aviation emissions are from flights to Spain outside the rail study area (mostly the Spanish Islands). While some of those passengers will need to visit those specific locations, the majority will likely be travelling for a "beach holiday" and so could potentially be switched from a flight to Mallorca to a train to Malaga. There are opportunities for the UK Government to develop a decarbonisation strategy for international holidays by promoting domestic and near-Europe destinations with package holidays that include rail tickets rather than flights.

Fourth, the rapid growth in flights to major hub airports such as Dublin, Amsterdam, and Dubai suggest that many passengers are connecting onto other flights. Quantifying this effect from the data used in this paper is not possible, but it is likely to be substantial. For example, a passenger that flies from London to Sydney via Dubai hides 68 % of their passenger-kms from this analysis.

Finally, whilst addressing the quality and cost of the rail network (relative to air travel) will be key, there are also other interventions that might encourage air-rail switching, including the introduction of more direct services; addressing cross-Channel capacity issues; encouraging sleeper trains, package deals and prebooking; and improving links with Ireland.

While this paper has focused on the UK aviation market, it has shown how origin–destination data about aviation demand can generally highlight opportunities for modal shift and decarbonisation. While the specific details of travel demand will vary between countries, the methods will likely be generalisable, especially in Europe.

Funding

The authors gratefully acknowledge support from UK Research and Innovation through the Centre for Research into Energy Demand Solutions; grant reference number EP/R 035288/1 and Energy Demand Research Centre; grant reference number EP/Y010078/1.

CRediT authorship contribution statement

Malcolm Morgan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Zia Wadud:** Conceptualization, Funding acquisition, Writing – review & editing. **Sally Cairns:** Conceptualization, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data will be deposited with the UK Data Service https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=857557.

References

Aamaas, B., Peters, G.P., 2017. The climate impact of Norwegians' travel behavior. Travel Behav. Soc. 6, 10–18. https://doi.org/10.1016/j.tbs.2016.04.001.
Andersson, E., Lukaszewicz, P., 2006. Energy consumption and related air pollution for Scandinavian electric passenger trains. Stockholm.
Avogadro, N., Cattaneo, M., Paleari, S., Redondi, R., 2021. Replacing short-medium haul intra-European flights with high-speed rail: Impact on CO2 emissions and regional accessibility. Transp. Policy 114, 25–39. https://doi.org/10.1016/j.tranpol.2021.08.014.
Baumeister, S., Leung, A., 2021. The emissions reduction potential of substituting short-haul flights with non-high-speed rail (NHSR): The case of Finland. Case Stud. Transp. Policy 9, 40–50. https://doi.org/10.1016/j.cstp.2020.07.001.
Bearne, S., 2023. Why sleeper trains are being revived across Europe. BBC News.
Beevor, J., Murray, L., 2019. jet, set, go: The case for electric-only UK private jet flights from 2025. London.
BEIS, 2022a. Government conversion factors for company reporting of greenhouse gas emissions [WWW Document]. URL https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting (accessed 8.16.22).
BEIS, 2022b. Final UK greenhouse gas emissions national statistics: 1990 to 2020. London.
Bergantino, A.S., Capozza, C., Capurso, M., 2015. The impact of open access on intra- and inter-modal rail competition. A national level analysis in Italy. Transp. Policy 39, 77–86. https://doi.org/10.1016/j.tranpol.2015.01.008.
Börjesson, M., 2014. Forecasting demand for high speed rail. Transp. Res. Part A Policy Pract. 70, 81–92. https://doi.org/10.1016/j.tra.2014.10.010.
Briginshaw, D., 2020. Air France ordered to curb competition with rail in France [WWW Document]. Int. Railw. J. URL https://www.railjournal.com/passenger/high-speed/air-france-ordered-to-curb-competiton-with-rail-in-france/ (accessed 2.3.23).
Büchs, M., Mattioli, G., 2021. Trends in air travel inequality in the UK: From the few to the many? Travel. Behav. Soc. 25, 92–101. https://doi.org/10.1016/j.tbs.2021.05.008.
CAA, 2019. Passenger survey report 2019. Crawley.
CAA, 2022b. Flight punctuality [WWW Document]. URL https://www.caa.co.uk/data-and-analysis/uk-aviation-market/flight-punctuality/ (accessed 10.20.22).
CAA, 2022a. UK airport data, Tables 12.1 - 12.3 [WWW Document]. URL https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/ (accessed 10.20.22).
Cairns, S., Newson, C., Boardman, B., Anable, J., 2006. Predict and decide: Aviation, climate change and UK policy. Environmental Change Institute, University of Oxford", Oxford.
CAPA, 2016. US immigration pre-clearance: Dublin Airport's rapid growth has been supported by enhanced US access [WWW Document]. URL https://centreforaviation.com/analysis/reports/us-immigration-pre-clearance-dublin-airports-rapid-growth-has-been-supported-by-enhanced-us-access-282568 (accessed 12.9.22).
Cass, N., 2021. Social and material cogs of the needs satisfier escalator. ECEEE Summer Study Proc. 47–57.
Cass, N., 2022. Hyper-aeromobility: the drivers and dynamics of frequent flying. Consum. Soc. XX 1–23. https://doi.org/10.1332/LCWC4408.
CCC, 2021. 2021 Report to Parliament. London.
DECC, 2019. UK greenhouse gas emissions statistics: Methodology Summary. London.
DfT, 2017. UK Aviation Forecasts. London.
DfT, 2022. Jet Zero Strategy: Delivering net zero aviation by 2050. London.
Diaconu, L., 2012. The Evolution of the European Low-cost Airlines'Business Models. Ryanair Case Study. Procedia - Soc. Behav. Sci. 62, 342–346. https://doi.org/10.1016/j.sbspro.2012.09.054.
Dobruszkes, F., Dehon, C., Givoni, M., 2014. Does European high-speed rail affect the current level of air services? An EU-wide analysis. Transp. Res. Part A Policy Pract. 69, 461–475. https://doi.org/10.1016/j.tra.2014.09.004.
Dobruszkes, F., Mattioli, G., Mathieu, L., 2022. Banning super short-haul flights: Environmental evidence or political turbulence? J. Transp. Geogr. 104, 103457. https://doi.org/10.1016/j.jtrangeo.2022.103457.
Dobruszkes, F., Peeters, D., 2019. The magnitude of detours faced by commercial flights: A global assessment. J. Transp. Geogr. 79, 102465. https://doi.org/10.1016/j.jtrangeo.2019.102465.
Doomernik, J.E., 2016. Competitive position of high-speed rail in Western Europe, in: 14th World Conference on Transport Research : WCTR 2016, 10-15 July, 2016, Shanghai, China. Elsevier B.V., pp. 1–20.
Dyson, P., Sutherland, R., 2021. Transport for Humans. London Publishing Partnerships, London.
Eccles, M., 2022. EU approves France's short-haul flight ban — but only for 3 routes. Politico.
EEA, 2024. Greenhouse gas emission intensity of electricity generation in Europe [WWW Document]. URL https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1?activeAccordion=546a7c35-9188-4d23-94ee-005d97c26f2b (accessed 8.16.24).
Eurocontrol, 2019. Fuel Tankering: economic benefits and environmental impact. Brussels.
European Commission, 2020. Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4). Brussels.
European Commission, 2023. Trans-European Transport Network (TEN-T) [WWW Document]. URL https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en (accessed 2.3.23).
European Parliament, 2007. Air Transport Agreement - Annexes - Declarations - Protocol, Statute Number 25.5.2007 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A22007A0525%2801%29.
Flightradar24, 2022. About Flightradar24 [WWW Document]. URL https://www.flightradar24.com/about (accessed 10.25.22).
Geofabrik, 2021. Europe [WWW Document]. URL http://download.geofabrik.de/europe.html.
Georgiadis, P., 2023. 'We are full': the rebirth of Europe's sleeper trains. Financ, Times.

Getlink, 2023. Maintenance [WWW Document]. URL https://www.getlinkgroup.com/en/our-group/eurotunnel/maintenance/ (accessed 7.18.23).
Givoni, M., 2006. Development and impact of the modern high-speed train: A review. Transp. Rev. 26, 593–611. https://doi.org/10.1080/01441640600589319.
Givoni, M., Dobruszkes, F., Lugo, I., 2012. Uncovering the Real Potential for Air–Rail Substitution: An Exploratory Analysis. In: Nderwildi, O., King, S. (Eds.), Energy, Transport, & the Environment. Springer, London, London, pp. 495–512. https://doi.org/10.1007/978-1-4471-2717-8_27.
Gössling, S., Humpe, A., 2020. The global scale, distribution and growth of aviation: Implications for climate change. Glob. Environ. Chang. 65. https://doi.org/10.1016/j.gloenvcha.2020.102194.
Grimme, W., Maertens, S., 2019. Flightpath 2050 revisited – An analysis of the 4-hour-goal using flight schedules and origin-destination passenger demand data. Transp. Res. Procedia 43, 147–155. https://doi.org/10.1016/j.trpro.2019.12.029.
GSA, 2021. Fly America Act [WWW Document]. URL https://www.gsa.gov/policy-regulations/policy/travel-management-policy/fly-america-act (accessed 10.21.22).
Gu, H., Wan, Y., 2022. Airline reactions to high-speed rail entry: Rail quality and market structure. Transp. Res. Part A Policy Pract. 165, 511–532. https://doi.org/10.1016/j.tra.2022.09.016.
Hoon, G., 2009. Britain's Transport Infrastructure.
HS2, 2023. London to West Midlands [WWW Document]. URL https://www.hs2.org.uk/the-route/high-speed-network-map/ (accessed 2.3.23).
IEA, 2022. Transport. Paris.
ITV, 2020. Visitors spend estimated £145.9m in Guernsey during 2019 [WWW Document]. ITV News. URL https://www.itv.com/news/channel/2020-02-28/visitors-spend-estimated-145-9m-in-guernsey-during-2019 (accessed 2.20.23).
Jansson, K., Nelldall, B.-L., 2010. High-speed trains in Sweden – a good idea ? *. In: 12th World Conference for Transportation Research, pp. 1–20.
Visit Jersey, 2023. Monthly Passenger Arrivals [WWW Document]. URL https://business.jersey.com/research-trends/tourism-statistics/monthly-passenger-arrivals/ (accessed 2.20.23).
Jungbluth, N., Meili, C., 2019. Recommendations for calculation of the global warming potential of aviation including the radiative forcing index. Int. J. Life Cycle Assess. 24, 404–411. https://doi.org/10.1007/s11367-018-1556-3.
Karpman, J., 2022. Brace for Impact: The Environmental and Economic Effects of Shifting Passenger Travel from Airplanes to High-Speed Rail. Los Angeles. https://doi.org/10.17610/T6N593.
Klenner, J., Muri, H., Strømman, A.H., 2022. High-resolution modeling of aviation emissions in Norway. Transp. Res. Part D Transp. Environ. 109, 103379. https://doi.org/10.1016/j.trd.2022.103379.
Knowles, R., Farrington, J., 1998. Why has the market not been created for Channel Tunnel regional passenger rail services? Area 30, 359–366. https://doi.org/10.1111/j.1475-4762.1998.tb00080.x.
Larsson, J., Kamb, A., Nässén, J., Åkerman, J., 2018. Measuring greenhouse gas emissions from international air travel of a country's residents methodological development and application for Sweden. Environ. Impact Assess. Rev. 72, 137–144. https://doi.org/10.1016/j.eiar.2018.05.013.
Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J., Gettelman, A., De León, R.R., Lim, L.L., Lund, M.T., Millar, R.J., Owen, B., Penner, J.E., Pitari, G., Prather, M.J., Sausen, R., Wilcox, L.J., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmos. Environ. 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834.
Limb, L., 2021. It's official: France bans short haul domestic flights in favour of train travel. euronews.
Miyoshi, C., Givoni, M., 2013. The Environmental Case for the High-Speed Train in the UK: Examining the London–Manchester Route. Int. J. Sustain. Transp. 8, 107–126. https://doi.org/10.1080/15568318.2011.645124.
NAO, 2020. High Speed Two: A progress update. London.
National Railway Museum, 2023. Mallard: The world's fastest steam locomotive [WWW Document]. URL https://www.railwaymuseum.org.uk/whats-on/mallard-worlds-fastest-steam-locomotive (accessed 2.3.23).
Nelldal, B.-L., Andersson, E., 2012. Mode Shift as a Measure to Reduce Greenhouse Gas Emissions. Procedia - Soc. Behav. Sci. 48, 3187–3197. https://doi.org/10.1016/j.sbspro.2012.06.1285.
Olugbenga, O., Kalyviotis, N., Saxe, S., 2019. Embodied emissions in rail infrastructure: a critical literature review. Environ. Res. Lett. 14, 123002. https://doi.org/10.1088/1748-9326/ab442f.
ORR, 2021. Rail Emissions. London.
Park, Y., O'Kelly, M.E., 2016. Origin–destination synthesis for aviation network data: examining hub operations in the domestic and international US markets. J. Adv. Transp. 50, 2288–2305. https://doi.org/10.1002/atr.1459.
Puliafito, S.E., 2023. Civil aviation emissions in Argentina. Sci. Total Environ. 869, 161675. https://doi.org/10.1016/j.scitotenv.2023.161675.
Quadros, F.D.A., Snellen, M., Sun, J., Dedoussi, I.C., 2022. Global Civil Aviation Emissions Estimates for 2017–2020 Using ADS-B Data. J. Aircr. 59, 1394–1405. https://doi.org/10.2514/1.C036763.
Rajendran, S., Popfinger, M., 2022. Evaluating the substitutability of short-haul air transport by high-speed rail using a simulation-based approach. Transp. Res. Interdiscip. Perspect. 15, 100632. https://doi.org/10.1016/j.trip.2022.100632.
Rapid Transition Alliance, 2022. European sleeper trains are waking up [WWW Document]. URL https://www.rapidtransition.org/stories/european-sleeper-trains-are-waking-up/ (accessed 3.24.23).
Reiter, V., Voltes-Dorta, A., Suau-Sanchez, P., 2022. The substitution of short-haul flights with rail services in German air travel markets: A quantitative analysis. Case Stud. Transp. Policy 10, 2025–2043. https://doi.org/10.1016/j.cstp.2022.09.001.
Ros, M., 2023. Europe is trying to ditch planes for trains. Here's how that's going, CNN.
Sausen, R., Isaksen, I., Grewe, V., Hauglustaine, D., Lee, D.S., Myhre, G., Köhler, M.O., Pitari, G., Schumann, U., Stordal, F., Zerefos, C., 2005. Aviation radiative forcing in 2000: An update on IPCC (1999). Meteorol. Zeitschrift 14, 555–561. https://doi.org/10.1127/0941-2948/2005/0049.
Schäfer, A.W., Barrett, S.R.H., Doyme, K., Dray, L.M., Gnadt, A.R., Self, R., O'Sullivan, A., Synodinos, A.P., Torija, A.J., 2018. Technological, economic and environmental prospects of all-electric aircraft. Nat. Energy 4, 160–166. https://doi.org/10.1038/s41560-018-0294-x.
Teter, J., Kim, H., 2022. Aviation Tracking report — September 2022. Paris.
Thomas, I., 2022. United Airlines is aiming to have electric planes flying by 2030. CNBC.
Topham, G., 2023. Eurostar trains forced to run with empty seats due to Brexit passport rules. Guard.
Tran Dinh, B., 2022. How far can you go by train in 5h? [WWW Document]. URL https://www.chronotrains.com/ (accessed 12.6.22).
Walker, P., 2021. Boris Johnson's plan for Irish Sea bridge rejected over £335bn cost. Guard.
Wittle, F., 1930. Improvements relating to the propulsion of aircraft and other vehicles. GB347206A.
World Bank, 2020. Air transport, passengers carried [WWW Document]. URL https://data.worldbank.org/indicator/IS.AIR.PSGR?most_recent_value_desc=true (accessed 2.3.23).
Zhang, A., Wan, Y., Yang, H., 2019. Impacts of high-speed rail on airlines, airports and regional economies: A survey of recent research. Transp. Policy 81, A1–A19. https://doi.org/10.1016/j.tranpol.2019.06.010.