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*Research Article*

# Passenger Aviation and High Speed Rail: A Comparison of Emissions Profiles on Selected European Routes

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Air transport has been constantly growing and forecasts seem to confirm the trend; the resulting environmental impact is relevant, both at local and at global scale. In this paper, data from various datasets have been integrated to assess the environmental impact of modal substitution with high speed rail. Six intra-EU28 routes and a domestic route have been defined for comparison. The airports have been chosen considering the share of the total number of passengers on flights to/from other EU Member States. Three scenarios have been proposed in the time period 2017–2025; aircraft types, distance bands, and occupancy rate are investigated on each scenario. The comparison with HSR service has been carried out only on passenger service and not for freight. The energy consumption and the consequent emissions for the aircraft have been estimated on the base of the available data for the mix of aircraft types, performing the routes. The results indicate the advantage of the high speed trains, in terms of direct $CO_{2eq}$ emissions per passenger km. Compared to a neutral scenario, with an annual passenger increment of 3.5%, the HSR substitution of the 5% and the 25% of this increment allow a GHG saving of 4% and 20%, respectively. Some of the analysed routes (e.g., Frankfurt Main–Paris CDG) have interesting GHG savings but the duration of the trip today is limiting for a real substitution. Moreover, there is general agreement that the extreme weather events induced by climate change will affect the functioning of the European transport system. In this sense, transportation by the rail mode is expected to play a significant role in strengthening the EU transport system, its resilience, and its reliability, as it is less immediately subject to the impacts of severe weather conditions.

## 1. Introduction

Transport impacts EU citizens' daily life, directly affecting life quality in many ways. The energy consumption of the EU-28 entire transport sector in 2015 has been 358.6 Mtoe, accounting for the 33% of the total EU-28 primary energy consumption: 1084 Mtoe [1]. Road transport is the most relevant segment (82.0%) with a consumption of about 293.9 Mtoe today followed by the international aviation segment (12.8%) 45.7 Mtoe, whereas the domestic aviation (1.54%) and rail (1.73%) account for 5.54 Mtoe and 6.22 Mtoe, respectively.

The total number of passengers travelling by air in the European Union in 2016 has been estimated in 973 million, with an increment of about 5.9% compared to 2015; 47% of total passengers moved to/from Intra-EU-28 airports, with an increment of 10.2% with respect to 2015 (Table 1).

In the last 25 years (1990–2015), inland waterways and rail recorded the largest decreases in energy consumption: 1.9 and 2.0 Mtoe reduction, respectively in EU-28 [1]. With the decline of rail transport becoming more evident, a stronger effort from various actors (EC, decision-makers, authorities, etc.) have been put in place to find solutions to increase sector competitiveness. In 2001, the EC released its "first Railway Package" and through the White Paper on Transport claimed its willingness to support rail revitalization [2]. Between 2002 and 2016 the second, third, and fourth Railway Packages have followed. Six legislative texts constitute the so called "fourth Railway Package," aiming to complete the single market for rail services (Single European Railway Area) [3] and also establishing the European Union Agency for Railways [4]. An interesting initiative is the Shift2Rail Joint Undertaking [5, 6]: it focuses on R&I and market-driven solutions for promoting the competitiveness of the European rail industry.

Table 1: Total number of passenger transport in EU-28 (source: [17].).

| EU-28 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Total transport | | National transport | | International intra EU-28 transport | | International extra EU-28 transport | |
| No. of passengers (in 1000) | Growth (%) 2015-2016 | Nr. of passengers (in 1000) | Growth (%) 2015-2016 | No. of passengers (in 1000) | Growth (%) 2015-2016 | No. of passengers (in 1000) | Growth (%) 2015-2016 |
| 972,693 | 5.9 | 168,676 | 4.6 | 457,422 | 10.2 | 346,596 | 1.4 |

In this framework, Shift2Rail sets the ambitious targets to double the capacity of the European rail system, increasing reliability and service quality by 50%, while increasing life-cycle performances; projects carried out under this Horizon 2020-JU initiative will support the completion of the Single European Railway Area (SERA).

Today the EU-28 total railway length is about 230,000 km but significant differences are present across the EU area. South-eastern countries (SEE) are facing a slow railway lines development: in 2012, Croatia had a total of 2,722 km, Serbia 3,809 km, and Bulgaria and Romania 4,098 and 10,785 km, respectively, while Germany has a total of 37,976 km of rail tracks, France 29,273, Spain 13,853, and UK 15,884 km ([7] EU TRANSPORT). Clearly the total rail length in a specific country is not the only way to measure the real level of service as, for instance, it is not directly connected with the population and its distribution on the overall country surface. Eurostat uses the ratio between the change in inland transported passenger and the constant price GDP. In the decade 2004–2014, inland passenger transport grew by 5% slower than constant price gross domestic product (GDP) in the EU-28, and significant reductions have been observed for Italy, Germany, Spain, and UK. By contrast, 11 Member States most notably Greece, Bulgaria, Estonia, and Romania have shown increases in passenger transport associated with a weak economic development [8].

The development of new rail lines in the EU is today driven by high speed rail (HSR) projects; high speed lines are part of the rail network of Belgium, Germany, Spain, France, Italy, the United Kingdom, the Netherlands, Austria, and Poland. In 2010, Europe had 6,214 km of high speed lines [9]; from 2010 and 2016 the high speed network expanded by 1,400 km (31%) and by 2030 the planned high speed Trans-European Transport Network (TEN-T: Figure 1) should extend HSR to over 30,000 Km [10].

The availability of High Speed Train (HST) lines opens the possibility of partial substitution with short-haul and medium-haul intra-EU flights. HSR services, either through modal competition or through cooperation, already exist among EU airports like Frankfurt Main, Paris CDG, Madrid Barajas, and Amsterdam Schiphol, which are all connected to the Trans-European HSR Network [11]. Despite the current state of development, the potential of HSR is still not fully exploited. One of the main aims for increasing the rail potential is the expected better environmental performance of this mode of transport: several studies defined the potential per-seat saving in emissions, achievable by substituting short-haul flights with HSTs [12, 13].


Figure 1: The EU Core Network Corridors (interactive maps at https://ec.europa.eu/transport/themes/infrastructure_en).

The environmental impacts of aircraft operations on local air pollution and climate change are considered almost linearly dependent on the flying time, the aircraft seat capacity, the engine efficiency, and thus the fuel consumption, to the modal share in the journey to/from the airport and to the distance of the airport from the city centre. Differently, HSR emissions depend mainly on the mix used for the electricity production, the route distance, seat occupancy, and the overall train efficiency, with a strong impact of the cruise speed. IATA [14] claims that aviation showed in 2013 occupancy rates of 80%, higher than those of other transport modes.

Although available literature agrees on the potential benefits of shifting air transport to rail, some authors argue that the introduction of new HSR services could have significant environmental impacts [15], mainly related to the medium and long-term impacts of the infrastructures realization, in terms of local biodiversity and habitats preservation [16]. D'Alfonso et al. [11] modelled the environmental impacts of London-Paris HSR-air transport competition, capturing the effects of induced demand, schedule frequency, and HSR speed: the authors showed that the net environmental effects can be negative since there is a negative trade-off due to the substitution effect.

The aim of the present work is to investigate the GHG potential reduction by substituting shares of intra EU-28 flights with HSR services, in the time period between 2017 and 2025. The analysis is carried out for a specific set of city pairs, considering that a total of 730 million passengers passed through the top 20 passenger airports in the EU in 2015 (approximately half of the total number of air passengers) [17]. In the paper the type of aircraft, the distance bands and the occupancy rate are varied to study potential scenarios. Freight has not been considered, as the airfreight is today accounting for a minor share of the overall EU-28 freight volume: in 2015, rail transport accounted for 18.3% of the EU total, while air mail and freight accounted in 2016 for 15,179 kton (0.9%) [18]. As final consideration, HSR is not used for freight; hence no comparison can be made with airfreight segment.

## 2. Material and Methods

The approach presented herein aims to integrate existing knowledge about the potential for modal substitution, with an environmental appraisal based on an analysis of the current European air transport sector trends.

*2.1. Potential for Substitution.* Rail transport can be a real alternative to aviation providing specific conditions. Modal split of passenger transport is usually defined as the percentage of each mode of transport, expressed in passenger-kilometres (PKM) and representing the transport of one passenger by a mode of transport over one kilometre. There are many factors contributing to the customer mode choice, among others: the cost of the travel, the safety standards, the comfort level, the frequency of the service and the accessibility of the terminals [20], the service reliability, and the time-efficiency. It is also highlighted by Dobruszkes [21] that the market answer to the introduction of specific high speed lines shows that the impact of HSR on air travel demand can be dramatic in some cases: on the Paris-Nantes route, the introduction of the TGV network decreased the air traffic share by 30%. In a recent report, UIC [22] claims that 80% of modal split with air services can be expected for HRS when travel time by train is less than 2.5 hours. According to Barrón et al. [23] the HSR link between Madrid and Seville shifted the air/rail passengers split from 67:33% to 16:84%. Even on an international trip, like the London-Paris route, HSR proves to be highly competitive with air [24]. Some authors, like Janic (Janic et al., 1993), consider HSR competitive with aviation over a range of distances of 400–2000 km, while others, like Rothengatter (Rothengatter et al., 2011), find evidence that real competition occurs for distance up to 1000 km, most likely between 400 and 800 km. Similar conclusions have been drawn by Chiara et al. [25], where indicatively 800 km is identified as a threshold under which trains systematically beat aircraft in terms of travel time; the author also pointed out that this figure may increase to 1,000 km in a scenario of greater HSR extension [25]. Sun et al. [15] consider a preferable range for HSR between 200 km and 1,000 km and, interestingly, enlarge it up to 2000 km with the option of high speed night-trains.

Due to the expected large increase in air transport demand, HRS could also get advantages from limited airport hub capacity [26]. For domestic interurban journeys under 300 km, air travel is not normally available and coach and rail fares tend to depend mainly on their relative speed and frequency [10].

Cost and time appear to be the most relevant influencing parameter with respect to modal shift. In the Study on Prices and Quality of Rail Passenger Services [27] an interurban trip over 300 km was compared with an international trip; the appraisal includes the time required for check-in and border controls. In most of the investigated cases, the resulting rail travel was faster than air travel and also less expensive; as an example the Paris-Lyon rail connection offers double average speed for half the price.

*2.2. Definition of the Target Distance Bands.* In this work, two ranges of distance bands are defined to compare aviation and rail services: six medium-haul intra EU-28, plus a national route. For defining the city pairs, EUROSTAT database has been used to obtain the number of passengers transported between EU airports [17]. Four airports have been chosen, mainly for their relative closeness in both distance term and considering flight times: no more than one and a half hours

(i) *LHE*: London Heathrow (in the United Kingdom), the busiest airport in the EU with a total of 75.0 million passengers carried in 2015,

(ii) *CDG*: Paris-Charles de Gaulle (France),

(iii) *FRA*: Frankfurt Main (Germany),

(iv) *AMS*: Amsterdam Schiphol (The Netherlands).

The potential of modal shift between these airports is relevant also considering that based on 2015 data, they represent close to half (47.9%) [17] of the total number of flown passengers to/from other EU Member States. In order to estimate the relative distance for both transport modes, distance calculators have been used [28–32] (see Tables 2 and 3).

In order to compare rail and air modes of transport on a domestic haul, the Italian Rome Fiumicino-Milan Linate route has been chosen. The expected flight duration on this route is 1:10 h, for a total flight distance of about 510 km. The rail service takes 3:00 h of the HSR, covering the distance of 620 km. On this trip, the time required for reaching the airports from the city centres is quiet relevant: the time required to reach Milan Linate (LIN) from Milan downtown (Milan railway Central station) is expected to be 50 min while the time needed to reach Rome downtown (Rome railway Termini station) from Fiumicino L. da Vinci International Airport (FCO) is about 45 min [32]: the total expected time for the air journey is therefore 2:45 h, without considering internal transfers.

EUROSTAT database [18] has been used to identify the number of passengers among the airports considered in this study. Another source of data is the EUROCONTROL Data Demand Repository (DDR) [33], which has been used to

Table 2: Relative distances for railways (∗) and air flights (∗∗).

| Distance: Rail/Flight [km] | London Heathrow (LHR) | Paris-Charles de Gaulle (CDG) | Frankfurt/Main (FRA) | Amsterdam/Schiphol (AMS) | Rome Fiumicino (FCO) | Milano Linate (LIN) |
|---|---|---|---|---|---|---|
| London Heathrow (LHR) | | 480* | 800* | 565* | -* | -* |
| Paris-Charles de Gaulle (CDG) | 348** | | 570* | 485* | -* | -* |
| Frankfurt/Main (FRA) | 655** | 450** | | 450* | -* | -* |
| Amsterdam/Schiphol (AMS) | 372** | 400** | 365** | | -* | 470* |
| Rome Fiumicino (FCO) | -** | -** | -** | -** | | |
| Milano Linate (LIN) | -** | -** | -** | -** | 562** | |

Table 3: Relative journey duration for railways (∗) and air flights (∗∗).

| Duration: HST/Flights [h:mm] | London Heathrow (LHR) | Paris-Charles de Gaulle (CDG) | Frankfurt/Main (FRA) | Amsterdam/Schiphol (AMS) | Rome Fiumicino (FCO) | Milano Linate (LIN) |
|---|---|---|---|---|---|---|
| London Heathrow (LHR) | | 3:05* | 6:30* | 5:30* | -* | -* |
| Paris-Charles de Gaulle (CDG) | 1:15** | | 5:00* | 3:15* | -* | -* |
| Frankfurt/Main (FRA) | 1:30** | 1:15** | | 4:30* | -* | -* |
| Amsterdam/Schiphol (AMS) | 1:20** | 1:20** | 1:15** | | -* | -* |
| Rome Fiumicino (FCO) | -** | -** | -** | -** | | 1:10* |
| Milano Linate (LIN) | -** | -** | -** | -** | 3:00** | |

extract data on the flights, carried out in a specific period. To handle a manageable amount of data, a sample from two representative weeks of the yearly traffic has been downloaded: week 24 and week 37, which are typically recognized by airline industries as representative of the overall year [34, 35]. In this paper this database has been used only to identify the type of aircraft used in each country for a specific distance band, to calculate the relative emissions. The data can be segmented, for each country, in order to be summarized for distance bands and aircraft type. A distance segmentation in three bands is proposed in this study, even if almost entirely the investigated cases are in the first segment, with one single case in the second:

(i) up to 500 km

(ii) 500–1000 km

(iii) >1000 km.

As indicated in Table 2 all the reference airports considered in the study are represented by the first segment (<500 km), with the exception of the Frankfurt Main–London Heathrow route.

*2.3. Aircraft Type, Consumption, and $CO_2$ Emissions.* In order to estimate the air transport emissions on the identified routes, the aircraft type has to be taken into account. The aircraft market is characterized by a small number of manufacturers with a high level of competition. Technology is a key parameter for this sector and focus is today on energy efficiency: EASA [36] reported that between 2005 and 2014 the aviation emissions increased by 5%, far below the increment in the PKM. Moreover, even with the current relatively low oil prices, fuel is still one the most relevant parts of the airlines expenses: 18% of the total costs [37]. According to Boing Current Market Outlook 2016 [38], the aircraft in service by the European airlines were, at the end of the year 2015, about 5,400. The different information sources give very similar numbers of aircraft, but they are typically segmented in nonhomogeneous categories. Databases like EUROSTAT define the passenger aircraft based on number of seats: <50 seats, 50–150 seats, 150–250 seats, and >250 seats. Another type of segmentation uses the maximum take-off weight (MTOW): up to 7 ton MTOW (small aircraft), 7–136 ton MTOW (medium size), and >136 ton MTOW (large aircraft); nevertheless this definition is more significant when air freight is considered. Yet another possible segmentation, based on the studies used in this work, combines the number of seats with the number of the aisles:

(i) Small regional jets (SJ): up to 100 seats-single aisle

(ii) Narrow bodies (NB): > 100 seats-single aisle

(iii) Small wide bodies: up to 300-twin aisle

(iv) Medium wide bodies: between 300 and 400 seats-twin aisle

(v) Large wide bodies: > 400 seats-twin aisle

On the defined distance bands, all below the 1000 km, regional jet (mostly turboprops) (SJ) and narrow body (NB) aircraft constitute the larger share. In regard to the number of available seats per flight, the current trend is to reduce the SJ in favour of the NB [39, 40]: increment of the size of aircraft on regional routes, with models of 100 or more seats (i.e., CRJ 1000, CS-100, Embraer E190E2 and 195E2). This is particularly true in the EU and the USA [41], even if other authors suggest an unclear trend at global level [15].

In the present work the number of flights among the reference airports has been segmented for the two aircraft types (SJ and NB), and by means of the Corinair database [42] the fuel consumption has been evaluated. The fuel consumption per aircraft type has been estimated for the standard LTO cycle (take-off, climb, approach, and taxi-in) plus the cruise phase over the remaining distance. The $CO_2$ emissions can be calculated multiplying the fuel consumption—expressed in kg of Jet A1—by 3.15, according to the EU ETS Directive [43].

*2.4. Emission Impact of Rail Transport.* Energy performance profiles and the associated emissions for rail transport are mainly related to the type of energy used: diesel engines and electrical units are the two options currently used in the railway sector. In HSR only electricity is used and consequently the emissions are a direct function of the primary energy mix. Additionally to primary energy production, electric trains also emit particles originating from wear of rails, brakes, wheels, and carbon contact strips [44].

Energy consumption of passenger rail services shows a wide range of values, due to the extreme differences in the performance of the rolling stock, as well as to the different operational features, such as speed. A review carried out by Politecnico di Torino [45] defined a range of consumption between 0.022 kWh/PKM, for express regional trains with few stops, and 0.175 kWh/PKM, for services like the undergrounds, characterized by high mass and frequent stops, that show energy requirements even higher than those of HSTs. In regard to HST, in 2011 the TOSCA project [46] set the average consumption for a 510 seats train, with 65% occupancy, at 0.061 kWh/PKM. More recently, Chiara et al. [25] presented specific energy consumption figures for several HST models in service among the EU routes, indicating an average consumption of 0.037 kWh/seat km.

Similarly to other studies [47, 48] and commercial experiences [49], an average occupancy rate of the 65% is here considered, and using the Dalla Chiara average figure, the final specific energy consumption of HST results in 0.057 kWh/PKM; this figure is in good agreement with other previous studies [11, 50].

Table 4: Carbon intensity of *medium-voltage electricity* [19].

| Country | CI of electricity consumed at MV (with Upstream) $gCO_2$/kWh |
|---|---|
| BE | 262 |
| DE | 602 |
| FR | 101 |
| IT | 417 |
| NL | 558 |
| UK | 599 |

Table 5: Route-specific $CO_2$ emission factor.

| Country | Carbon Intensity $gCO_2$/kWh |
|---|---|
| CDG-LHE | 315.8 |
| AMS-FRA | 589.6 |
| AMS-LHE | 436.9 |
| CDG-AMS | 263.5 |
| FRA-CDG | 351.3 |
| FRA-LHE | 448.2 |
| FCO - LIN | 417.0 |

The potential emissions advantage of the HSR compared to aircraft is strongly affected by the mix of primary energy sources used for the electricity generation. In this study, the carbon intensity of each country crossed by the train routes has been estimated. Data from Moro and Lonza [19] have been used to define the $gCO_{2eq}$/kWh of the medium-voltage infrastructure (Tables 4 and 5).

The direct $CO_2$ emissions for the energy production are not the only impact of the rail sector; the indirect effects of rail infrastructure construction include the emissions for building the new line but also the effects on landscape, townscape, biodiversity, and heritage [51]. The International Union of Railways [52] proposes to consider an additional 5 g $CO_2$/PKM in order to include infrastructure manufacture and maintenance.

Another important difference between the air transport mode and the rail is indeed the average length of the routes for the same journey. The air distances are the shortest ones between each pair of cities and rail distances result usually is 35% longer; those percentages become smaller when distances significantly increase. Nevertheless, there is agreement that climate change will affect European aviation sector in short and medium term [36]. The expected direct effects are numerous, among others: more frequent heavy rains, higher air temperatures, and stronger storms; these can influence regularity of flights, also having implications for flying the most environmentally efficient routes. On the other hand, the rail sector is expected to suffer less for these effects, having an intrinsically higher resilience to adverse weather conditions, despite the risk of power supply disruptions in the event of extreme weather conditions.

Table 6: Passengers per route [18].

| Total Passenger | Q1 | Q2 | Q3 | Q4 | *2016* | Avg. no. of seats per flight | Avg. no. flights per day between airports | Avg. no. flights per day between depart. from an airport |
|---|---|---|---|---|---|---|---|---|
| FRA - CDG | 187,875 | 252,851 | 257,267 | 208,012 | 906,005 | 111 | 22 | 11 |
| FRA - LHE | 313,271 | 372,597 | 445,089 | 355,334 | 1,486,291 | 132 | 30 | 15 |
| CDG - LHE | 292,477 | 302,119 | 328,266 | 286,296 | 1,209,158 | 111 | 30 | 15 |
| AMS-FRA | 171,202 | 220,802 | 228,343 | 197,167 | 817,514 | 111 | 20 | 10 |
| AMS-CDG | 274,414 | 305,629 | 312,083 | 295,213 | 1,187,339 | 111 | 30 | 15 |
| AMS-LHE | 366,226 | 411,487 | 428,219 | 411,238 | 1,617,170 | 111 | 40 | 20 |
| FCO - LIN | 298,097 | 328,741 | 258,073 | 303,627 | 1,188,538 | 132 | 24 | 12 |

*2.5. Scenario Definition.* In order to estimate the potential GHG savings achievable by shifting passengers from air transport to HSR, a growth pace for aviation sector has to be defined. According to Alonso et al. [34] in the period 2021–2030 a constant 3.5% growth rate can be expected for the European area; this prediction is substantially confirmed by IATA, which sets at 3.7% annually the Compound Average Growth Rate (CAGR) in its 20-Year Air Passenger Forecast [53]. Assuming therefore an annual growth rate of 3.5%, three scenarios are defined:

(i) Business as Usual (BAU) scenario, baseline: none of the expected aviation passenger growth (on the analysed routes) is shifted to HSR service.

(ii) High-rail scenario: 25% of the expected aviation passenger growth (on the analysed routes) is shifted to HSR service.

(iii) Low-rail scenario: only 5% of the expected aviation passenger growth (on the analysed routes) is shifted to HSR service.

All scenarios aim to represent the expected trend in the next coming years, assuming the used average growth as representative of the period 2017–2025. The BAU scenario describes a rail sector where the actual market trend is not inverted by means of significant new investments or by clear and effective policy support. In the low-rail scenario some actions are taken, but the time required to make them effective (e.g., new HSR lines, improvements of the current infrastructure) is longer than the time horizon chosen for the analysis; thus only minor effects can be expected. In the high-rail scenario, all the stakeholders focus their efforts in trying to catch a significant share of the aviation expected growth, by means of political, commercial, and infrastructural commitments. In the optimistic scenario considerable actions are taken, such as fares reductions achievable by means of aggressive market strategies and/or as the effect of taxation reductions and other incentives (e.g., customer loyalty campaigns, focusing on points collection, discounts for car rental, or accommodation).

## 3. Results and Discussion

*3.1. Air Mode Emissions.* In Table 6 the number of passengers travelling between the airport pairs is reported, with respect to 2016 quarters. For each distance band, the average number of flights per day has been calculated, assuming an average number of seats per flight which is representative of the mix of the two considered aircraft (SJ and NB): in order to validate the assumptions, the results have been double-checked directly on the airport website (i.e., [54]). As reported, the considered domestic flight between Rome Fiumicino airport and Milan Linate is carried out only with narrow body aircraft (NB), with more than 100 seats.

Table 7: Fuel consumption and $CO_2$ emission per route.

| Route | Distance | Avg. fuel consumption | Avg. $CO_2$ emissions | |
|---|---|---|---|---|
| - | km | ton | ton | g/PKM |
| CDG-LHE | 348 | 1.75 | 5.51 | 143 |
| AMS-FRA | 365 | 1.50 | 4.72 | 116 |
| AMS-LHE | 372 | 1.63 | 5.14 | 124 |
| CDG-AMS | 400 | 1.88 | 5.91 | 133 |
| FRA-CDG | 450 | 1.76 | 5.56 | 111 |
| FRA-LHE | 655 | 2.79 | 8.79 | 102 |
| FCO - LIN | 510 | 2.73 | 8.61 | 128 |

The average fuel consumption on each route is influenced by the different mix of small regional jet (SJ) and narrow body (NB) aircraft, which depends on the available fleet of the airlines performing the service. The total fuel consumption and $CO_2$ emissions have been calculated based on the aircraft mix elaborated by EUROCONTROL DDR data and considering an emission factor of 3.15 [43]. As shown in Table 7, the fuel consumption is relevant in particular for the shorter distances, where the LTO cycle more significantly affects total consumption. $CO_2$ emissions per passenger km are in line with the fuel consumption trend. A good performance is obtained by the national route among Milan and Rome airports, due to large aircraft and high seat occupancy rates.

Among the considered city pairs, the highest emission resulted for the Paris CDG–London Heathrow, even if the highest share of small jet respect to larger aircraft is for the Paris CDG–Amsterdam Schiphol route (Figure 2).

*3.2. Rail Mode Emissions.* The specific $CO_2$ emission of HST is related to the carbon intensity of the electricity production

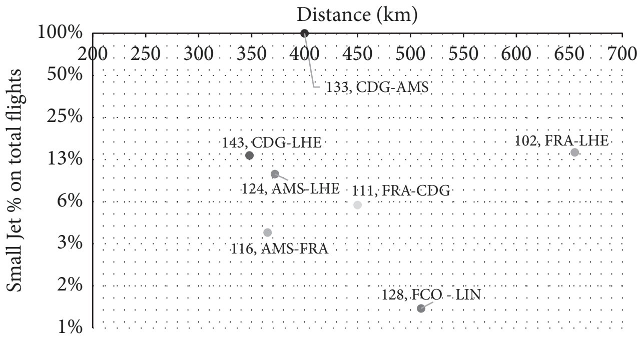


Figure 2: $CO_2$ emissions as function of the distance and the Small Jet to Narrow Body share ($gCO_2$/PKM).

Table 8: Specific carbon intensity of each route.

| Route | $gCO_2$/kWh avg | $gCO_2$/PKM |
|---|---|---|
| CDG-LHE | 315.8 | 18.0 |
| AMS-FRA | 589.6 | 33.6 |
| AMS-LHE | 436.9 | 24.9 |
| CDG-AMS | 263.5 | 15.0 |
| FRA-CDG | 351.3 | 20.0 |
| FRA-LHE | 448.2 | 25.6 |
| FCO - LIN | 417.0 | 23.8 |

and transport along the lines, considering the medium-voltage supply of the rail infrastructure. The specific emission factor of each route has been calculated on the base of the medium-voltage electricity carbon intensity, of the relevant countries crossed by the route. In Table 8 results show that the Amsterdam Schiphol–Frankfurt Main is the most impacting route (per PKM), whereas all the routes crossing France have the best performance, due to the low carbon intensity of electricity in France.

*3.3. Scenario Results.* The emission factors obtained show remarkable advantages of the rail mode compared to aviation, in terms of $gCO_2$ per passenger km; nevertheless, trains always have longer distances to cover with a subsequent possibility of lower passenger per km rate. Thus, the previously described scenarios have been used to compare these two modes on the chosen EU city pairs.

In the BAU scenario (Table 9), the expected impact of the foreseen growth accounts for 15.9 kton of CO2, on the selected routes. By displacing a share of this expected growth from the air to the rail mode, a direct saving can be achieved in both other scenarios. On the low-rail scenario (Table 10), a displacement of 5% of the increment allows for a saving of 4%. In the high-rail scenario (Table 11), 25% of the expected passenger increment is shifted to HSR, and the impact $CO_2$ saving ranges from the 16% of the Amsterdam Schiphol–Frankfurt Main route to 21.6% of the Amsterdam Schiphol–Paris CDG. Some routes, like the Frankfurt Main–Paris CDG, show an interesting GHG saving but the duration of the trip today makes a real substitution unlikely: increasing the average train speed could potentially fill the gap but that would also partly reduce the environmental advantages at the same time.

## 4. Conclusions

In this paper, data from various databases have been integrated in order to assess the environmental impact of modal substation among six intra-EU28 routes and one national route. The cities and the relative airports have been chosen considering that 730 million passengers (approximately half of total passengers on EU-domestic flights) passed through the top 20 airports in the EU in 2015.

The energy consumption and the resulting emissions of aircraft have been estimated on the base of the available data for the fleet mix servicing the routes. The results here presented confirm a remarkable advantage of high speed trains compared to aircraft, with regard to direct $CO_{2eq}$ emissions per PKM. Three scenarios have been proposed to define the effects produced by modal shift. Starting from a business as usual (BAU) scenario, where the allocation of the 3.5% annual pace of passenger growth remains unvaried towards 2025, two additional scenarios are calculated assuming the shift of the same annual growth rate to high speed rail by 5% in the low-rail scenario and 25% in the high-rail scenario. Scenario computation proves that shifting passengers to HST allows GHG savings of 4% and 21.6% in the low-rail and high-rail scenarios respectively. Some of the analysed routes (e.g., Frankfurt Main–Paris CDG) have interesting GHG saving but the duration of the trip by train today limits a real substitution; increasing the average train speed could potentially fill the gap but that would at the same time reduce the environmental benefits. In fact, although several authors indicate advantages for HSR on routes of up to 800 km (or even up to 1000 km), the present work considered a low demand for connections longer than 500 km and 5 h, at least in the short term. Improvements are expected not only in new types of rolling stock, providing comfortable transportation capacity for increasing numbers of passengers, but also to safe and efficient operation, as well as shared track and corridor operations [55].

Apart from energy efficiency considerations, a relevant medium term advantage of HSR deals with transport resilience to adverse weather conditions. There is in fact general agreement that climate change will affect the functioning of the European transport system [36], specifically for aviation. With respect to foreseeable direct impacts, impediments for flying the most environmentally efficient routes are expected. In this sense, transportation by the rail mode is expected to play a significant role in strengthening the EU transport system and its reliability, as it is less subject to the impacts of severe weather conditions.

Based on existing literature, converging conclusions are considerably limited with respect to the evaluation of the impacts for the two transport modes analysed in this paper. Additional research is needed aiming to widen the environmental impact categories considered. For instance, non-$CO_2$ related emissions (i.e., contrail cirrus, soot, etc.) are considered of particular relevance for the medium term deployment of the aviation sector [56]. In that respect, a comprehensive

Table 9: BAU scenario with 3.5% annual growth and zero shifting between the modes.

| Total Passenger | | Total $CO_2$ | Annual passengers increase | Annual $CO_2$ increase | Passenger to Rail | $CO_2$ Rail | $CO_2$ saved respect to aviation | $CO_2$ Balance | |
|---|---|---|---|---|---|---|---|---|---|
| | 2016 | ton | - | ton | | ton | ton | ton | % |
| FRA - CDG | 906,005 | 45,343 | 31,710 | 1,587 | 0 | 0.0 | 0.0 | 0.0 | 0.0% |
| FRA - LHE | 1,486,291 | 98,933 | 52,020 | 3,463 | 0 | 0.0 | 0.0 | 0.0 | 0.0% |
| CDG - LHE | 1,209,158 | 59,987 | 42,321 | 2,100 | 0 | 0.0 | 0.0 | 0.0 | 0.0% |
| AMS-FRA | 817,514 | 34,752 | 28,613 | 1,216 | 0 | 0.0 | 0.0 | 0.0 | 0.0% |
| AMS-CDG | 1,187,339 | 63,193 | 41,557 | 2,212 | 0 | 0.0 | 0.0 | 0.0 | 0.0% |
| AMS-LHE | 1,617,170 | 74,817 | 56,601 | 2,619 | 0 | 0.0 | 0.0 | 0.0 | 0.0% |
| FCO - LIN | 1,188,538 | 77,482 | 41,599 | 2,712 | 0 | 0.0 | 0.0 | 0.00 | 0.0% |

Table 10: Low-rail scenario with 3.5% annual growth and 5% shifting between the modes.

| Total Passenger | | Total $CO_2$ | Annual passengers increase | Annual $CO_2$ increase | Passenger to Rail | $CO_2$ Rail | $CO_2$ saved respect to aviation | $CO_2$ Balance | |
|---|---|---|---|---|---|---|---|---|---|
| | 2016 | ton | - | ton | | ton | ton | ton | % |
| FRA - CDG | 906,005 | 45,343 | 31710 | 1,587 | 1,586 | 18.1 | 79.4 | -61.3 | -3.9% |
| FRA - LHE | 1,486,291 | 98,933 | 52,020 | 3,463 | 2,601 | 53.2 | 173.1 | -120.0 | -3.5% |
| CDG - LHE | 1,209,158 | 59,987 | 42,321 | 2,100 | 2,116 | 18.3 | 105.0 | -86.7 | -4.1% |
| AMS-FRA | 817,514 | 34,752 | 28,613 | 1,216 | 1,431 | 21.6 | 60.8 | -39.2 | -3.2% |
| AMS-CDG | 1,187,339 | 63,193 | 41,557 | 2,212 | 2,078 | 15.1 | 110.6 | -95.5 | -4.3% |
| AMS-LHE | 1,617,170 | 74,817 | 56,601 | 2,619 | 2,830 | 39.8 | 130.9 | -91.1 | -3.5% |
| FCO - LIN | 1,188,538 | 77,483 | 41,599 | 2,712 | 2,080 | 42.5 | 135.6 | -93.1 | -3.4% |

Table 11: High rail scenario with 3.5% annual growth and 25% shifting between the modes.

| Total Passenger | | Total $CO_2$ | Annual passengers increase | Annual $CO_2$ increase | Passenger to Rail | $CO_2$ Rail | $CO_2$ saved respect to aviation | $CO_2$ Balance | |
|---|---|---|---|---|---|---|---|---|---|
| | 2016 | ton | - | ton | | ton | ton | ton | % |
| FRA - CDG | 906,005 | 45,343 | 31,710 | 1,587 | 7,928 | 90.5 | 396.8 | -306.3 | -19.3% |
| FRA - LHE | 1,486,291 | 98,932 | 52,020 | 3,463 | 13,005 | 265.8 | 865.7 | -599.8 | -17.3% |
| CDG - LHE | 1,209,158 | 59,986 | 42,321 | 2,100 | 10,580 | 91.4 | 524.9 | -433.5 | -20.6% |
| AMS-FRA | 817,514 | 34,751 | 28,613 | 1,216 | 7,153 | 108.2 | 304.1 | -195.9 | -16.1% |
| AMS-CDG | 1,187,339 | 63,193 | 41,557 | 2,212 | 10,389 | 75.7 | 552.9 | -477.3 | -21.6% |
| AMS-LHE | 1,617,170 | 74,817 | 56,601 | 2,619 | 14,150 | 199.1 | 654.6 | -455.5 | -17.4% |
| FCO - LIN | 1,188,538 | 77,483 | 41,599 | 2,712 | 10,400 | 153.3 | 678.0 | -524.72 | -19.3% |

parameter to assess the overall climate impacts of aviation, beyond the $CO_2$ emissions is acknowledged of relevance for the sector. Conversely, the environmental impacts of high speed rail seem to be better assessed by disaggregating impact categories, considering – for instance – the impact of HSR infrastructure on biodiversity, landscape, etc. [57]. On the other hand, one dimension which is relevant to both transportation modes is noise, where the definition of a comparable methodology could provide relevant information to scientists and decision-makers alike, when assessing their environmental performance beyond these modes' respective emissions profiles.

## Abbreviations

BAU: Business as usual
HSR: High speed rail
HST: High speed train
MTOW: Maximum take-off weight
NB: Narrow body aircraft
PKM: Passenger km
RPK: Revenue passenger km
SEE: South-Eastern European countries
SERA: Single European Railway Area
SJ: Small regional jet
TEN-T: Trans-European Transport Network.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Additional Points

*Highlights*. (1) Aviation to rail substitution effects are estimated for seven EU routes. (2) The routes chosen represent almost half of intra-EU aviation passengers. (3) Various datasets are integrated to perform the analysis. (4) Three scenarios are analysed to compare the effects of shifting passengers between air and rail transport in the time period 2017–2025. (5) GHG savings from 4% up to 21% can be achieved with high speed rail.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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