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How fast are rail trips between EU cities and is rail faster than air?

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How fast are rail trips between EU cities and is rail faster than air?

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ABSTRACT

This paper analyses rail speed on a set of 1 356 routes between medium and large EU cities located less than 500 km apart. On only 3 % of routes between these cities do rail speeds exceed 150 km/h and on 30 % of routes the speed is below 60 km/h. Rail speeds tend to be lower and more connections are missing in eastern EU Member States and on cross-border routes.

Out of 297 routes, served by both rail and a direct flight, the rail trip is faster on 68 of the routes. Improving operating speed to 160 km/h on the Trans-European Transport Network (TEN-T) core would increase this to 103. Operating speeds of around 175 km/h appear to be sufficient for rail-based trips to consistently outperform air trips on distances up to 500 km, but this is only necessary for longer trips.

A switch of air passengers to rail on routes where rail is faster would lead to a 17 % reduction in the total amount of CO_2 emissions from air trips on the 297 routes analysed, and a 4.2 % decrease in passenger travel time on these routes. If the speed on the TEN-T core network were to be improved, as proposed by the European Commission, such a modal switch would reduce CO_2 emissions on these routes by 25 % and travel times would decrease by 6 %. Such a modal switch would, however, require more than improvements in travel time alone and should consider issues such as cost, convenience, comfort and connecting flights.

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1. INTRODUCTION

Mobility is essential to economic and social development. Well-targeted infrastructure investment and network design are crucial for a transport system that provides accessibility to people and businesses, and for reducing regional disparities in connectivity.

Rail transport plays a key role in such a transport system and is an important priority under cohesion policy. For the 2014–2020 programming period, cohesion policy planned to inject a total of EUR 18 billion in rail projects throughout the EU (1). For the 2021–2027 programming period, planned investments in rail amount to another EUR 17 billion.

Despite the benefits of mobility, rail transport also involves costs to society. These include emissions of greenhouse gas and pollutants, but also accidents and congestion, all of which affect health and well-being. The EU transport strategy is focused on the transition to sustainable and smart mobility (2). This strategy proposes to significantly reduce greenhouse gas emissions, in part through a substantial shift to transport modes that produce less emissions.

In this respect, rail transport plays a crucial role. In its 2011 White Paper on transport, the Commission already proposed that the majority of medium-distance passenger transport should be done by rail by 2050 and that the length of the existing high-speed rail network should triple by 2030 (3). A key initiative in the current strategy involves a modal shift from air transport (4) towards greener modes of transport, including high-speed rail (5). In December 2021, the Commission adopted a proposal (6) for the revision of the TEN-T regulation, in which the Commission proposed, among other things: (i) a minimum speed for passenger rail on the core and extended core network of 160 km/h; and (ii) an expansion of the TEN-T high-speed rail network, with completion dates of 2030, 2040 and 2050 for the core network, the extended core network and the comprehensive network respectively.

This paper focuses on travel time, however, people consider many other factors when choosing how to travel, such as cost, reliability, comfort and safety. As a result, differences in travel time alone will not fully explain why people select a mode of transport. Nevertheless, travel time is widely recognised as an important factor influencing how people choose between air and rail travel (7). According to the literature, and depending on operating speed, boarding time (8), taxiing time and travel time to reach the airport or station (9), high-speed rail can be a viable alternative to air travel up to distances of 500 km (10).

This paper first investigates rail connections between all cities (11) in the EU that are less than 500 km apart and have at least 200 000 inhabitants (Section 2). Then it compares travel time between a subset of these cities, which can also be reached by a short flight (12), and identifies what factors explain when rail is faster. This is followed by a description of the impact of increasing rail speed and what the impact would be of people switching from air to rail travel on CO_2 emissions and travel times.

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(1) This represents more than a quarter of all cohesion policy investments in the transport sector. Another EUR 11.3 billion, almost entirely dedicated to rail investment, was transferred to the Connecting Europe Facility.

(2) European Commission (2020).

(3) European Commission (2011).

(4) Air transport has grown exponentially over the last years. Civil aviation, including international bunkers, is currently responsible for over 13 % of CO_2 emissions from transport at the EU level. Domestic civil aviation accounts for 1.4 % of emissions (European Commission, 2021).

(5) As defined in Council of the European Union (2003), high speed trains are trains designed in such a way as to guarantee safe, uninterrupted travel: (i) at a speed of at least 250 km/h on the lines specially built for high speed, while enabling speeds of over 300 km/h to be reached in appropriate circumstances; (ii) at a speed of the order of 200 km/h on existing lines which have been or are to be specially upgraded; and (iii) at the highest possible speed on other lines.

(6) European Commission (2021).

(7) See Dobruszkes (2011); Dobruszkes, Dehon and Givoni (2014); Xia and Zhang (2016); and Yang and Zhang (2012).

(8) The time between arrival at the airport or rail station and the actual departure.

(9) Rail stations tend to be located in or very close to urban areas and therefore tend to be more accessible than airports.

(10) Some authors consider a viable distance for high-speed rail to be up to 1 000 km, or even 2 000 km if night trains are considered (see, for example, Chiara et al., 2017; Sun, Zhang and Wandelt, 2017).

(11) For ease of reading, this paper uses 'city' to refer to an urban centre.

(12) The analysis in this section focuses on a comparison of travel times and does not look at other aspects relevant to transport mode choices, such as service frequency, transport prices, comfort and safety.

2. DOES RAIL CONNECT ALL MEDIUM AND LARGE CITIES IN THE EU?

In 2021, the Commission proposed an action plan to boost long-distance and cross-border passenger rail services. This builds on efforts by Member States to make connections between cities faster by better managing capacity, coordinating timetabling, creating facilities for sharing rolling stock and improving infrastructure to stimulate new train services, including at night (13). High-speed trains account for 31 % of total passenger kilometres by rail in the EU (14). In Spain and France, it is close to 60 %. However, over half of Member States do not have any high-speed railway lines.

This section analyses the 1 356 connections between EU cities that are located less than 500 km apart and have at least 200 000 inhabitants or are a national capital. For most of these connections, the straight-line speed (15) of the fastest train service (16) is low (Map 1). On only 3 % of these routes does the speed exceed 150 km/h (Table 1 and Figure 1). With 7.6 %, this share is the largest in southern Member States (17), where both Spain and Italy have a well-developed high-speed rail network. In north-western Member States, the total number of high-speed connections, which are mainly in Germany and France, is similar but their share is smaller. Because of higher population density, the rail network is denser, consisting of more short-distance connections where rail speeds tend to be lower. Nevertheless, north-western Member States have the largest share of rail connections faster than 90 km/h, and only a few city pairs without rail connection. The rail network is less developed in eastern Member States, with no connections with speeds above 150 km/h and a rail speed below 60 km/h on 60 % of the routes. Furthermore, 1 out of 5 city pairs in eastern Member States has no rail connection.

Table 2 shows a list of city pairs with missing connections, sorted by the product of the two populations, which can serve as a rough proxy for the latent demand of travel on the route in question. Nearly all routes between two capital cities in our dataset are served by a rail connection. This also holds for eastern Member States, where Warsaw–Vilnius was the only such route without a rail connection (although in December 2022, a direct train service was launched on this route). Some of the entries in the table concern routes between two relatively small cities where demand for transport may not be sufficient to justify a rail connection.

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(13) European Commission (2020).

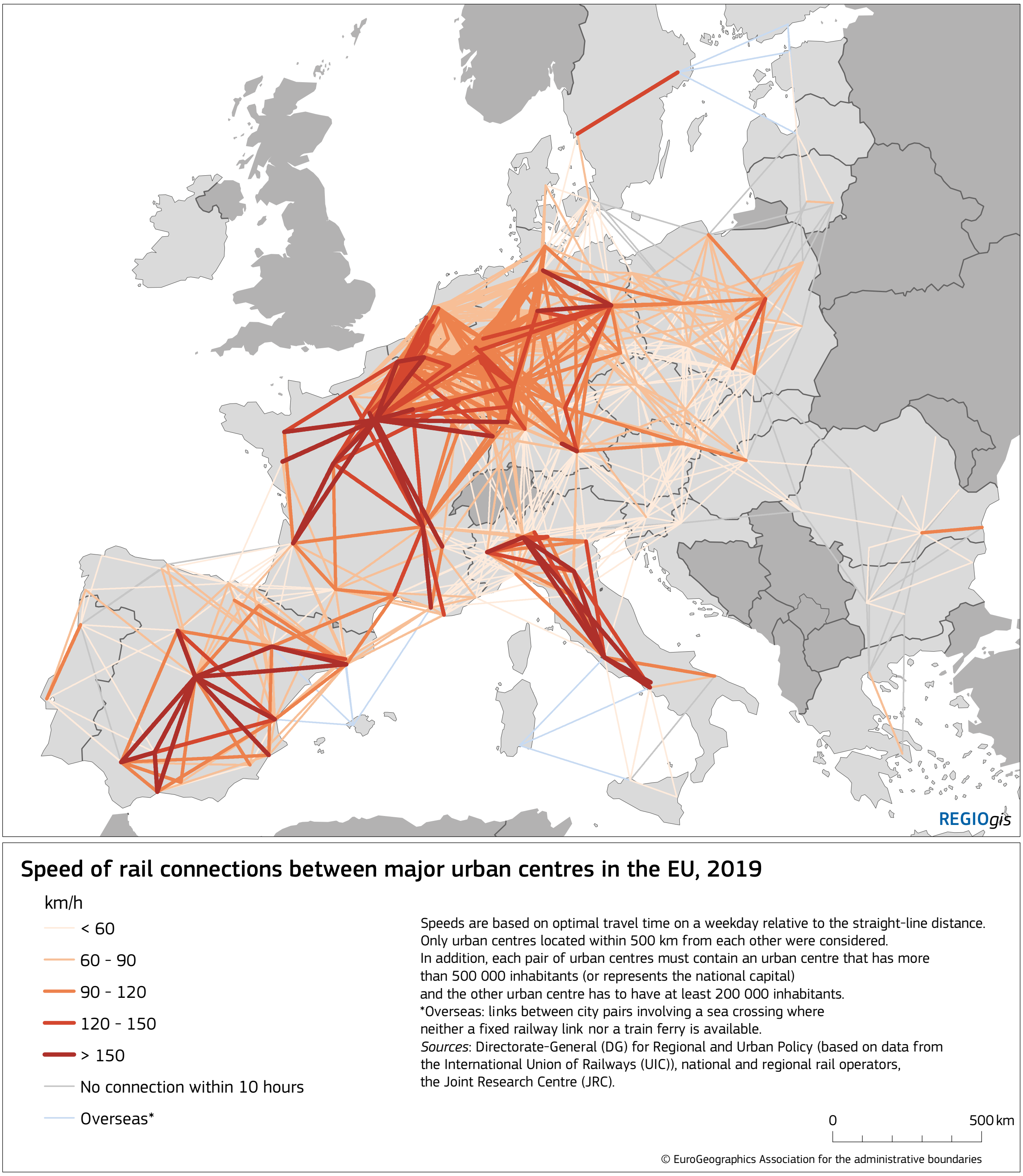
(14) This figure relates to all high-speed trains including tilting trains able to travel at 200 km/h, which do not necessarily require high-speed infrastructure.

(15) The straight-line speed used in this section is defined as the travel time between stations divided by the straight-line distance. Straight-line speeds are determined not only by the rail operating speed, but also by the time spent in transfer, and the 'detouring' factor. As such, straight-line speed is always lower than operating speed. Note that for the smaller set of routes considered in Section 3, information about the actual distances over the rail and the time spent in transfer could be obtained, which allowed us to disentangle the actual train operating speeds, along with the other two components of the straight-line speed (see also footnote 28).

(16) The fastest service available for departure during a weekday in 2019 between 6:00 and 20:00.

(17) For the purpose of this study, we have divided the EU Member States into three macro regions where 'southern Member States' includes Greece, Spain, Italy, Cyprus, Malta and Portugal, 'north-western Member States' includes Belgium, Denmark, Germany, Ireland, France, Luxembourg, the Netherlands, Austria, Finland and Sweden, and 'eastern Member States' includes Bulgaria, Czechia, Estonia, Croatia, Latvia, Lithuania, Hungary, Poland, Romania, Slovenia and Slovakia. Note that a route is considered to be located in a specific macro region if both the origin and the destination city are located in the region in question. If only one of the two cities is located in the region in question, the route counts as half a route for the purpose of region-specific calculations.

Map 1: Speed of rail connections between major urban centres in the EU, 2019 (18)



Speeds are based on optimal travel time on a weekday relative to the straight-line distance.
Only urban centres located within 500 km from each other were considered.
In addition, each pair of urban centres must contain an urban centre that has more than 500 000 inhabitants (or represents the national capital) and the other urban centre has to have at least 200 000 inhabitants.
*Overseas: links between city pairs involving a sea crossing where neither a fixed railway link nor a train ferry is available.
Sources: Directorate-General (DG) for Regional and Urban Policy (based on data from the International Union of Railways (UIC)), national and regional rail operators, the Joint Research Centre (JRC).

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However, the list also includes a number of routes between capital cities and second-largest cities or other populous cities. The majority of these routes are (partly) in eastern Member States, including Bucharest–Thessaloniki, Athens–Plovdiv, Sofia–Thessaloniki, Bucharest–Plovdiv, Budapest–Lublin and Warsaw–Kaunas. Furthermore, nearly all of these routes are cross-border routes. On some routes, natural obstacles, such as mountain ranges or large rivers, explain the absence of a rail link. This is, for example, the case for Sofia–Thessaloniki, a route between the capital of Bulgaria and the second city of Greece, each housing more than 1 million inhabitants in their metropolitan area. Despite the fact that the distance on this route is only 232 km, there is no rail connection between the two cities.

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(18) Interactive versions of the maps in this paper can be accessed via the interactive viewer at: https://ec.europa.eu/regional_policy/assets/scripts/map/regio-gis-maps/public_transport/rail_vs_air.html. The viewer provides additional information and visualisations per map, along with additional maps on related topics.

Table 1: City pairs with a rail connection speed of at least 150 km/h, 2019

City A (larger)	City B (smaller)	Straight-line speed (km/h)
Paris	Bordeaux	239
Milan	Bologna	226
Paris	Strasbourg	225
Madrid	Saragossa	211
Bordeaux	Tours	209
Paris	Tours	206
Paris	Lyon	203
Paris	Rennes	203
Madrid	Barcelona	201
Paris	Lille	190
Paris	Brussels	190
Rome	Florence	188
Paris	Nancy	186
Madrid	Valencia	184
Barcelona	Saragossa	181
Paris	Karlsruhe	176
Madrid	Valladolid	174
Milan	Rome	173
Malaga	Cordoba	171
Madrid	Cordoba	171
Milan	Turin	170
Lyon	Marseille	170
Paris	Reims	169
Madrid	Malaga	169
Strasbourg	Reims	168
Naples	Rome	168
Berlin	Hanover	168
Seville	Cordoba	167
Paris	Nantes	167
Madrid	Seville	164
Naples	Florence	162
Paris	Grenoble	160
Milan	Florence	160
Brussels	Lille	159
Lyon	Cergy-Pontoise	159
Rome	Caserta	159
Madrid	Alicante	158
Berlin	Hamburg	157
Rome	Bologna	154
Strasbourg	Cergy-Pontoise	152
Munich	Augsburg	151

Source: DG Regional and Urban Policy.

Table 2: City pairs with no rail connection within 10 hours, 2019

City A (larger)	City B (smaller)	Product of populations (× 1 m)	Straight-line distance (km)
Bucharest	Thessaloniki	1 498 697	500
Athens	Plovdiv	1 038 787	468
Sofia	Thessaloniki	880 261	232
Warsaw	Vilnius	703 243	394
Bucharest	Plovdiv	627 164	279
Porto	Seville	591 230	481
Copenhagen	Poznań	551 625	467
Budapest	Lublin	485 748	488
Warsaw	Kaunas*	450 327	354
Copenhagen	Gdańsk	435 107	417
Sofia	Cluj-Napoca	356 379	455
Sofia	Timişoara	347 321	378
Sofia	Constanța	310 274	463
Copenhagen	Bydgoszcz	283 442	457
Sofia	Galați	274 257	489
Sofia	Braşov	250 705	379
Thessaloniki	Plovdiv	246 833	228
Riga	Gdańsk	232 640	450
Porto	Gijón	224 302	353
Cracow	Cluj-Napoca	208 210	452
Cracow	Timişoara	202 918	488
Thessaloniki	Craiova	197 061	417
Zagreb	Timişoara	196 448	407
Zagreb	Bergamo	182 392	493
Porto	Oviedo	178 764	330
Łódź	Kaunas	178 401	459
Gdańsk	Vilnius	171 373	432
Riga	Białystok	158 697	430
Bordeaux	Gijón	142 677	430
Vilnius	Lublin	126 498	426
Vilnius	Białystok	116 904	223
Gdańsk	Kaunas	109 740	348
Plovdiv	Timişoara	97 392	488
Plovdiv	Constanța	87 003	390
Cluj-Napoca	Constanța	84 172	485
Plovdiv	Craiova	82 465	253
Lublin	Kaunas	81 004	418
Varna	Iaşi	78 210	439
Plovdiv	Galați	76 904	454
Białystok	Kaunas	74 860	204
Cluj-Napoca	Galați	74 402	372
Bydgoszcz	Kaunas	71 488	436
Plovdiv	Braşov	70 300	397
Varna	Galați	67 439	247
Timişoara	Graz	66 324	468

* A direct train service was launched on this route in December 2022.

Source: DG Regional and Urban Policy.

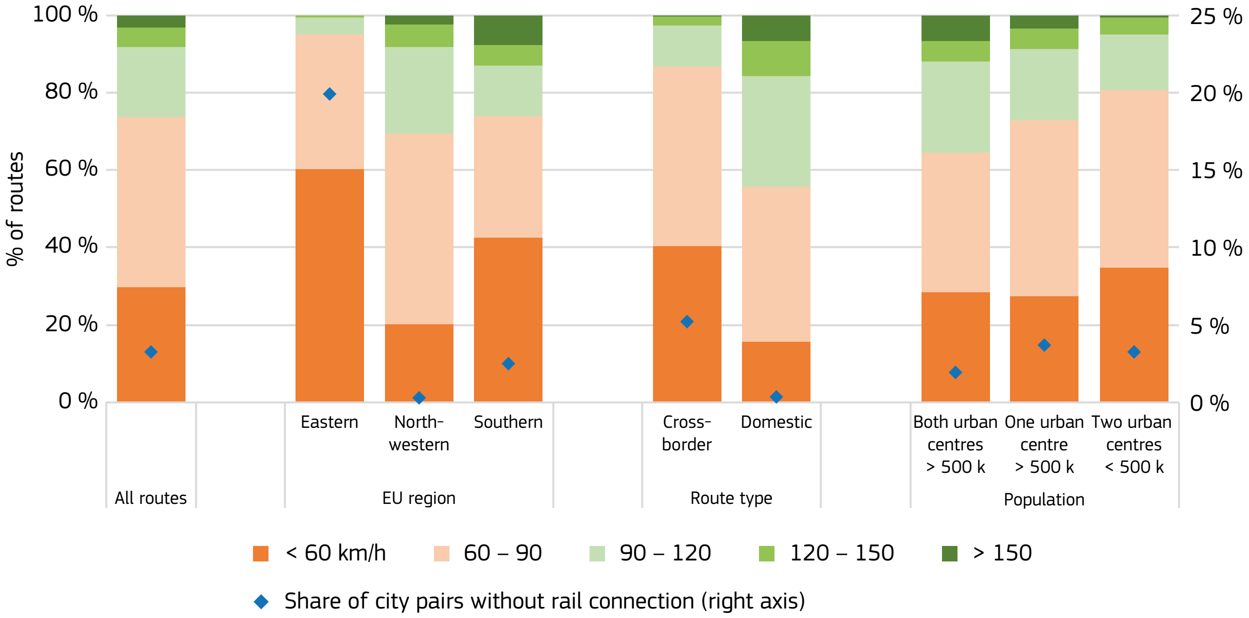

Figure 1: Speed of rail connections between urban centres, including by geographic region, by population size and by route type, 2019

NB: Only pairs of urban centres located within 500 km from each other are considered. In addition, urban centres have to have at least 200 000 inhabitants.

Source: DG Regional and Urban Policy.

Despite some progress towards technical interoperability, rail travel across EU borders is still hindered by many obstacles. The rail network has numerous gaps where national railways are not properly connected to each other (19). More than 5 % of cross-border city pairs lack a rail connection, against only 0.3 % of city pairs in the same country (20). Rail speeds on cross-border routes also tend to be lower than on domestic routes. On about 40 % of cross-border routes, rail speeds are below 60 km/h compared to only 16 % on domestic routes. Moreover, on only 0.4 % of cross-border routes do rail speeds exceed 150 km/h.

The share of routes with speeds above 150 km/h is larger among routes that connect large cities (i.e. with populations of over 500 000 (7 %)) than among routes between cities with populations of 200 000 – 500 000 (1 %) or between large and small cities (3 %). A similar difference is seen for the share of connections with speeds of over 90 km/h (36 % between large city pairs and 19 % between small ones).

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(19) Sippel, L. et al. (2018).

(20) It should be noted that these routes, whether cross-border or domestic, may be served by long-distance bus connections, which could be a reason for there being no rail connection.

3. IS TRAVEL BY RAIL OR BY AIR FASTER BETWEEN CITIES?

EU citizens tend to have good flight connectivity. On average, they have access to 556 flights per day within 90 minutes of driving time. In 2019, the total number of passenger trips on intra-EU-27 flights was 496 million. About one fifth of these, or 102 million trips, concerned routes with a distance of less than 500 km (21).

This section focuses on a subset of the 1 365 routes between the cities described above. It analyses 297 routes between cities that are served by a direct flight (22) and by a relatively direct rail connection. Of all the routes, only 313 had a direct flight connection. We dropped the 15 routes that required crossing a sea or ocean or a long detour such as Copenhagen–Gdańsk. We also dropped Vilnius–Warsaw, as the direct passenger rail service was foreseen to start only in December 2022 (23).

3.1. WHAT SHORT-HAUL FLIGHT ROUTES HAVE THE MOST PASSENGERS IN THE EU?

The 297 routes served by both rail and flights involve only 138 airport connections, since many airport connections serve more than one city pair. Demand for flights tends to be higher on connections, both domestic and cross border, in north-western Member States and domestic connections in some of the southern Member States (Map 2). On some of these connections the number of passengers exceeds 1 000 per day in each direction. Note that the data do not allow us to distinguish between passengers who use the short flight to connect to another flight and those who do not.

Given the high demand for trips on some of these connections, improving the rail connections between these cities could persuade more people to take the train. However, for many of the rail connections serving these routes, rail speeds lie below 120 km/h (Table 3 provides a list). The low rail speeds on these routes may help to explain the high demand for flights.

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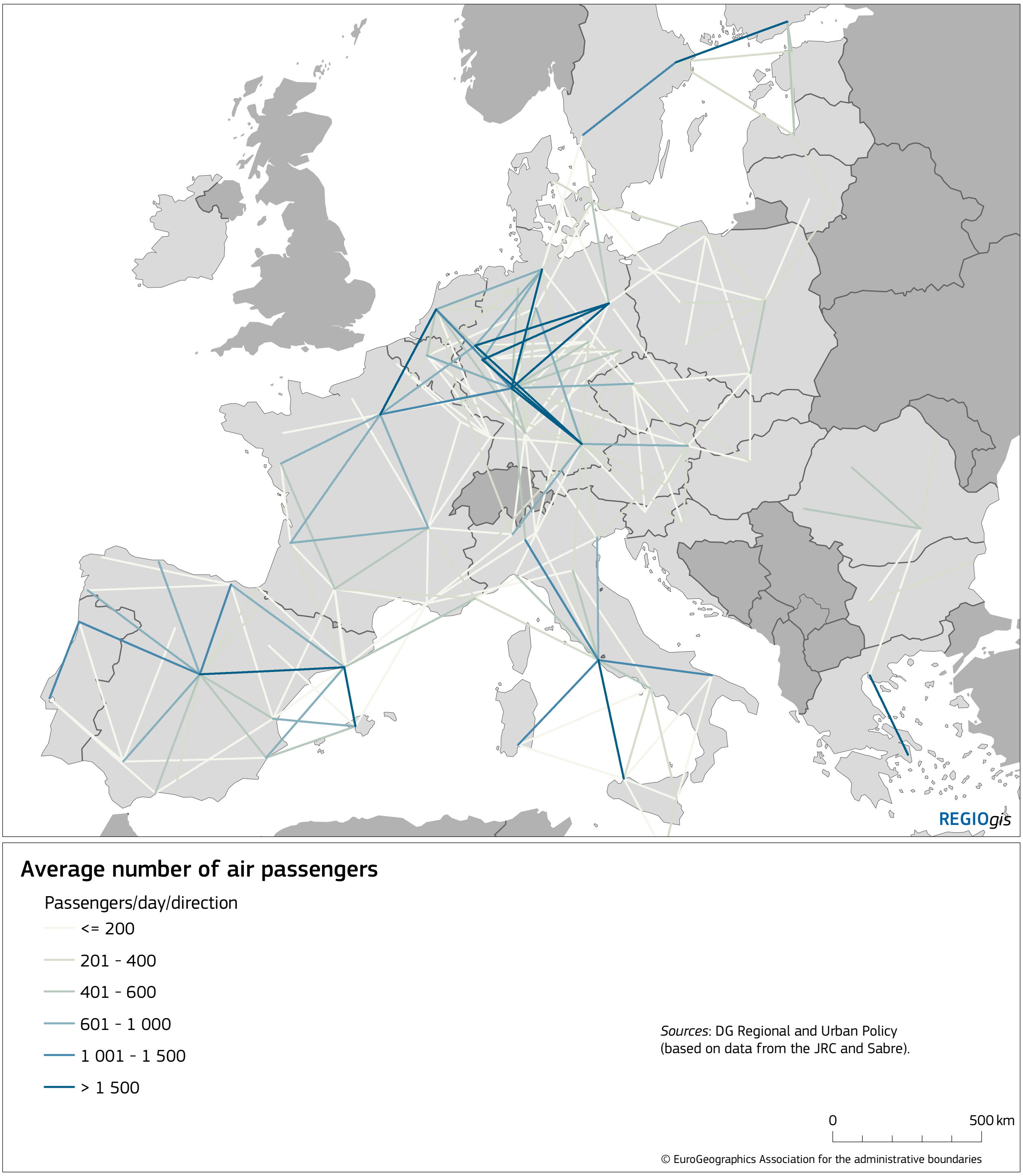
(21) DG Regional and Urban Policy (based on Eurostat).

(22) Based on information from Sabre airline data, these routes represent 57 million passenger trips per year. The difference with the 102 million trips from Eurostat data is, inter alia, explained by the application of filters regarding the minimum city size and the minimum number of flights and passengers per day in the Sabre data.

(23) Indeed, in December 2022 a direct train service was launched on this route.

Map 2: Average number of air passengers per day between EU airports, 2019 [24]



Sources: DG Regional and Urban Policy (based on data from the JRC and Sabre).

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[24] Interactive versions of the maps in this paper can be accessed via the interactive viewer at: https://ec.europa.eu/regional_policy/assets/scripts/map/regio-gis-maps/public_transport/rail_vs_air.html. The viewer provides additional information and visualisations per map, along with additional maps on related topics.

Table 3: Airport connections with more than 1 000 passengers per day where the speed of the corresponding rail connections is below 120 km/h

Airport connection (ICAO codes)	Corresponding rail connection(s) City A (larger) – City B (smaller)		Air passengers per day	Straight-line rail speed (km/h)
LIRF–LICJ	Rome	Palermo	2 153	40
LEMD–LPPR	Madrid	Porto	1 304	45
LEMD–LEBB	Madrid	Bilbao	1 136	62
LGAV–LGTS	Athens	Thessaloniki	1 703	74
EDDF– EHAM	Frankfurt am Main	Leiden, Rotterdam, The Hague, Amsterdam, Utrecht	1 260	83 – 93
LFPG-EHAM	Paris, Cergy-Pontoise	Utrecht, Leiden, Haarlem, The Hague, Amsterdam, Rotterdam	1 662	94 – 119
EDDM–EDDF	Munich	Frankfurt am Main	1 664	96
EDDM–EDDL	Munich	Ruhrgebiet, Solingen/Wuppertal, Düsseldorf, Cologne	2 192	96 – 104
LIRF–LIBD	Rome	Bari	1 050	101
LPPT–LPPR	Lisbon	Porto	1 375	102
EDDM–EDDK	Munich	Bonn	1 502	102
LPFG–EDDF	Paris, Cergy-Pontoise	Frankfurt am Main	1 464	103
EDDT–EDDK	Berlin	Bonn, Cologne	2 017	103 – 113
EDDT–EDDF	Berlin	Frankfurt am Main	3 296	112
EDDT–EDDL	Berlin	Krefeld, Düsseldorf	1 830	114
EDDH–EDDF	Hamburg	Frankfurt am Main	2 089	115

Sources: DG Regional and Urban Policy, the JRC (based on Sabre airline data).

3.2. WHICH TRIPS ARE FASTER BY RAIL THAN BY AIR?

This section compares the travel time of a trip by rail and by air and identifies factors that affect the relative travel time of each mode of transport. Comparing rail and air trips should go beyond the time spent on a train or on a plane and take account of the time needed to get to the airport or rail station, waiting times and actual departure and arrival times. While people flying spend less time on a plane compared to those taking the train, they spend more time travelling to and from the airport and at the airport (25). Trains can usually be boarded quickly and the train stations tend to be better connected to the city centre than airports (26). These 'out-of-vehicle' time components are either fixed (waiting/boarding) or otherwise independent of the distance of the trip (access to and from the station/airport). This means that rail tends to be relatively faster on shorter distance trips. This is clearly illustrated in Figure 2, which compares the composition of the total travel time of rail and air trips on three routes, representing different trip distances. For rail trips, a major part of the total travel time concerns in-vehicle time. Hence, the total trip time varies significantly depending on the trip distance. For air trips, the in-vehicle time is actually shorter than the other time components. Although the in-vehicle time varies with the trip distance, the total trip time of air trips shows much less variation. On the shortest of the three routes (i.e. the one between Florence and Rome) the rail trip is shorter than the air trip, mainly because of the relatively long out-of-vehicle time of the air trip. On the medium-distance route between Madrid and Granada the rail trip takes longer than the air trip, but the difference is small. On the longest distance route between Rotterdam and Strasbourg the air trip clearly outperforms the rail trip, due to the considerably longer in-vehicle time of the latter.

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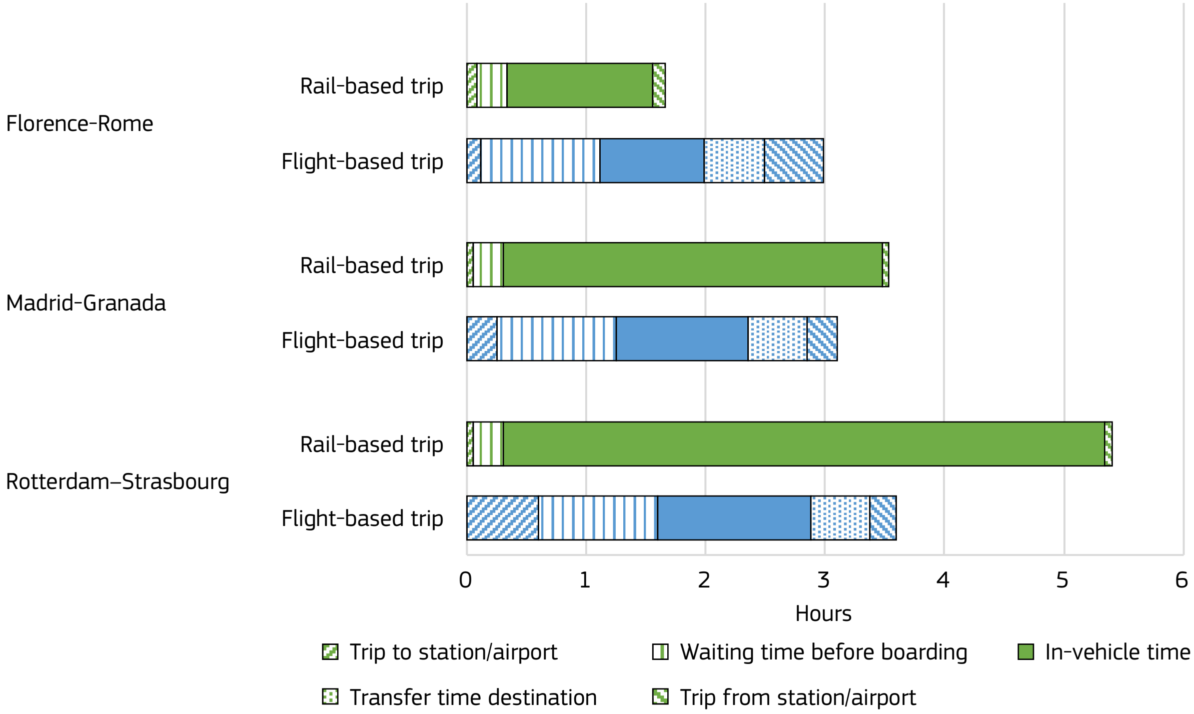
(25) The only exception in our dataset concerns the trip by airplane from Rotterdam to Antwerp, the in-vehicle component of which actually concerns a flight between Amsterdam and Brussels.

(26) The assumptions used for the present analysis are as follows. Time before boarding the first train: 15 minutes; check-in and boarding at the departure airport: 60 minutes; taxiing is assumed to be included in the flight time; transfer time at the arrival airport: 30 minutes. A flight speed of 500 km/h is assumed. If more than one connection between airports is available linking the same urban centres, the travel time of the connection with the highest number of passengers is taken.

Figure 2: Composition of city-to-city travel time for rail and air trips on selected routes, 2019

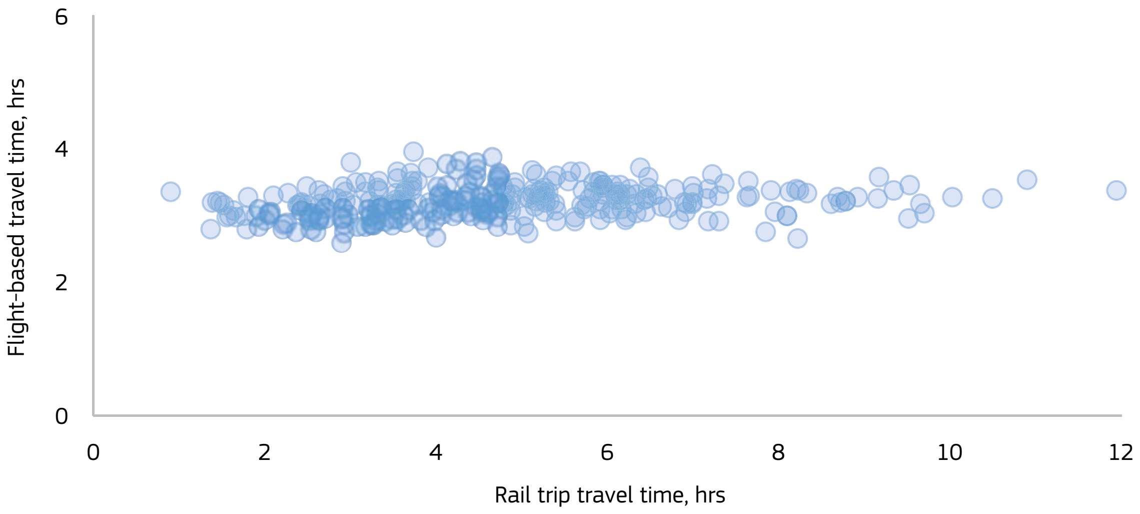


NB: Routes are selected to illustrate trips of different distances. Specifically, they are chosen as the routes closest to the bottom quintile, the median quintile and the last quintile of the distribution of distances between urban centres. The in-vehicle time includes the taxiing time.

Sources: DG Regional and Urban Policy, the JRC (based on Sabre airline data).

The difference in the variation in trip times is shown in Figure 3, which plots rail and air travel times. For the routes in our dataset, the duration of rail trips varies between 0.9 and 12.0 hours, with an average length of 4.8 hours. For air trips, the variation is much smaller, ranging between 2.6 and 4.0 hours. The average travel time of air trips is also considerably shorter at 3.2 hours, suggesting that rail trips may be more likely to outperform flights on a subset of mainly shorter distance routes.

Figure 3: Distribution of travel times of rail and air trips, 2019

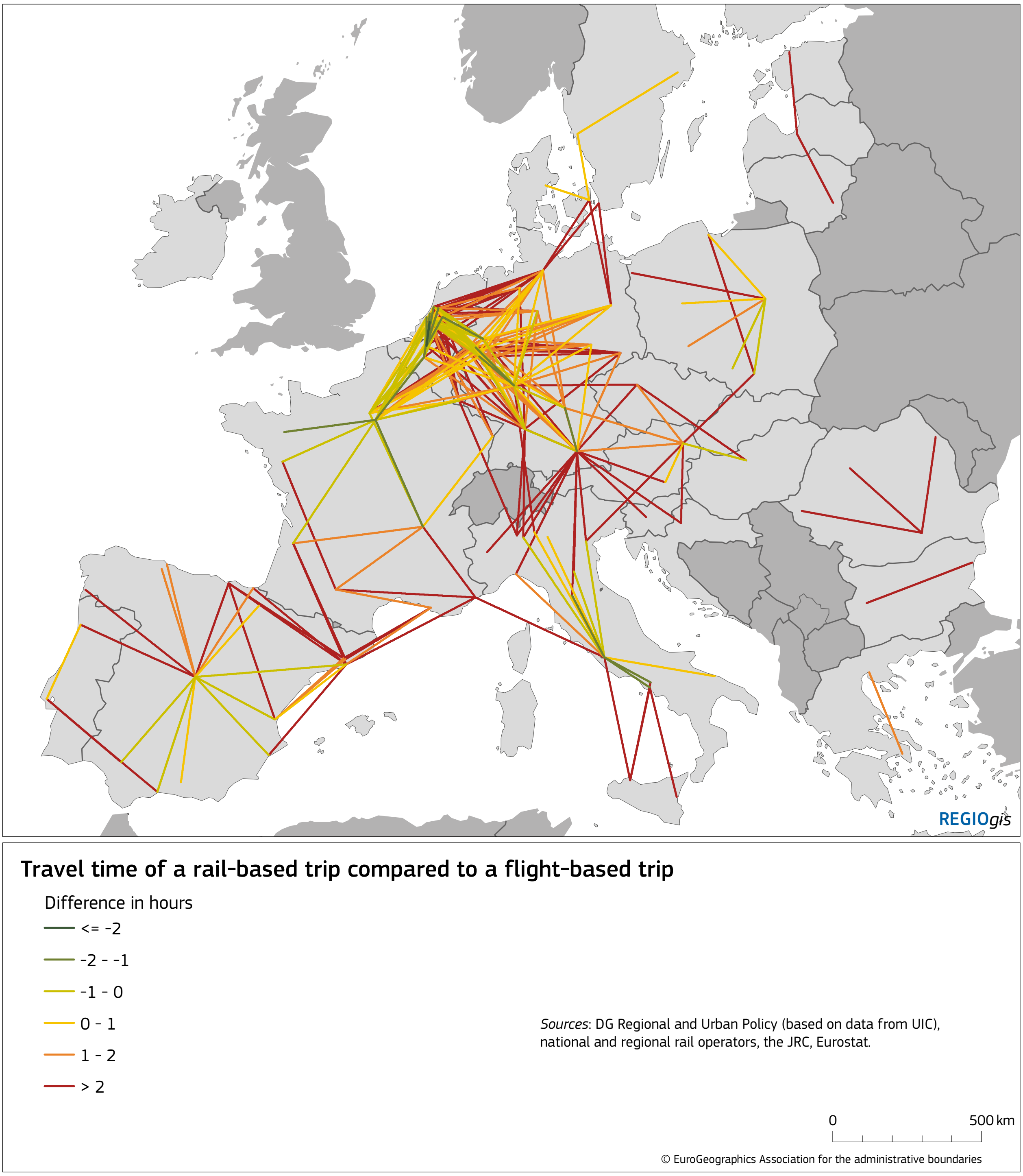


Sources: DG Regional and Urban Policy, the JRC (based on Sabre airline data).

By comparing the travel time of rail and air trips for each of the 297 routes in our dataset, we find that on 68 of these routes, the total travel time by rail is shorter than that by air. These routes mainly concern connections between cities in Belgium, Germany, France and the Netherlands, both domestic and international (Map 3). Many of these routes connect capital cities to other (capital) cities in a different country, but they also include various connections between non-capital cities. In addition, on some of the domestic routes in Spain, Italy and Poland rail is faster, but these are all connections between the capital city and other major cities in the country. Finally, on the route between Vienna and Budapest a rail trip is also faster than an air trip.

On 17 of the routes where the rail trip is faster, the travel time advantage is of an hour or more (Figure 4). These routes are mainly in and between Belgium, Germany, France and the Netherlands, but they also include three domestic routes in Italy.

Map 3: Travel time of a rail-based trip compared to a flight-based trip, 2019 [27]



Sources: DG Regional and Urban Policy (based on data from UIC), national and regional rail operators, the JRC, Eurostat.

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NB: Negative values indicate that the rail-based trip is faster than the flight-based trip.

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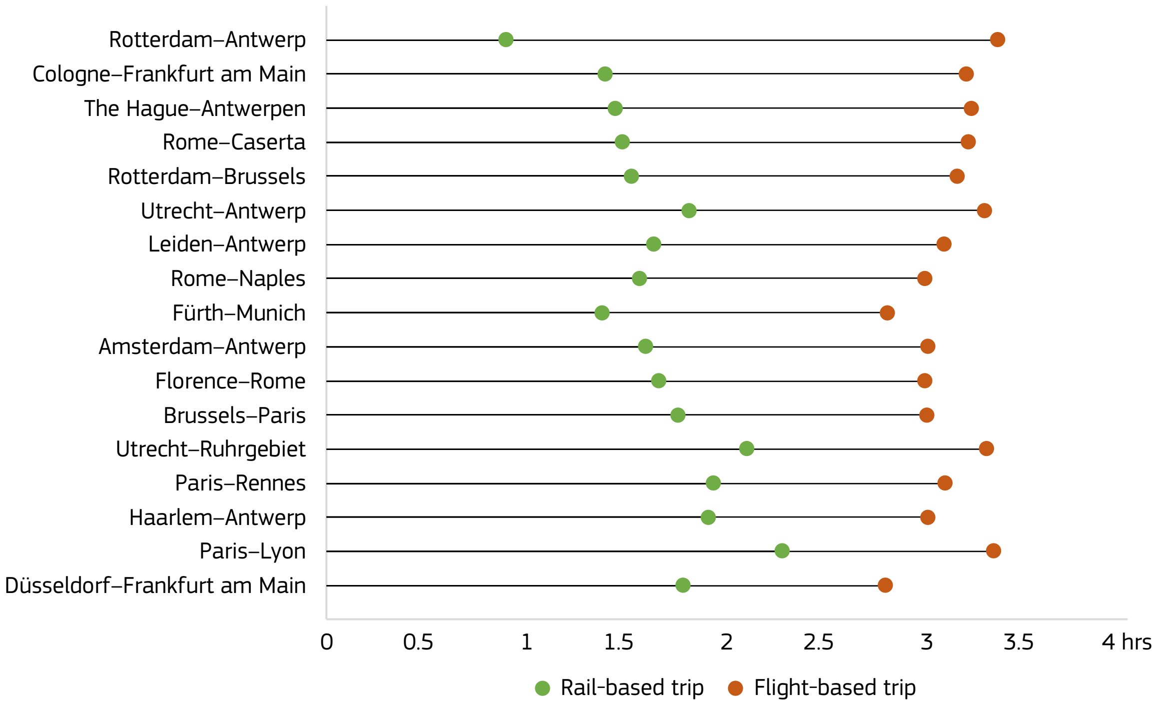
[27] Interactive versions of the maps in this paper can be accessed via the interactive viewer at: https://ec.europa.eu/regional_policy/assets/scripts/map/regio-gis-maps/public_transport/rail_vs_air.html. The viewer provides additional information and visualisations per map, along with additional maps on related topics.

Figure 4: Total travel time by rail and air on selected routes, 2019



NB: Routes are ranked by the difference in travel time between rail and air.

Sources: DG Regional and Urban Policy, the JRC (based on Sabre airline data).

3.3. WHY ARE SOME TRIPS FASTER BY RAIL THAN BY AIR?

On the routes where a rail trip outperforms an air trip, the average distance between the city pair is shorter than on other routes. This holds in particular for the set of routes in Figure 4, for which the average distance is only 177 km. This confirms our conjecture that rail trips are more likely to outperform flights on shorter distance routes, which is also clearly shown in Figure 5a. Air trips tend to outperform rail for distances of over 300 km. However, there are still many routes over 300 km where the reverse is the case. This indicates that rail has the potential to also compete with aviation successfully on relatively long distances, provided that a sufficient train operating speed can be achieved. For the routes considered here, operating speeds (28) of 175 km/h appear to be sufficient for rail trips to consistently outperform flights (Figure 5b). On some routes, lower rail speeds are sufficient, although these tend to be shorter distance routes.

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(28) Operating speed is calculated as the in-vehicle travel time minus the transfer time, divided by the rail-based distance. Note that this contrasts with the concept of straight-line speed used in Section 2, which is determined not only by the operating speed, but also by the time spent in transfers and the detouring factor. As such, the operating speed is always higher than the straight-line speed (see also footnote 15).

Figure 5: Difference in travel time by rail as opposed to air according to distance between city pairs and average rail operating speed, 2019

NB: Negative values on the vertical axis indicate that the total travel time by rail is less than that by air.

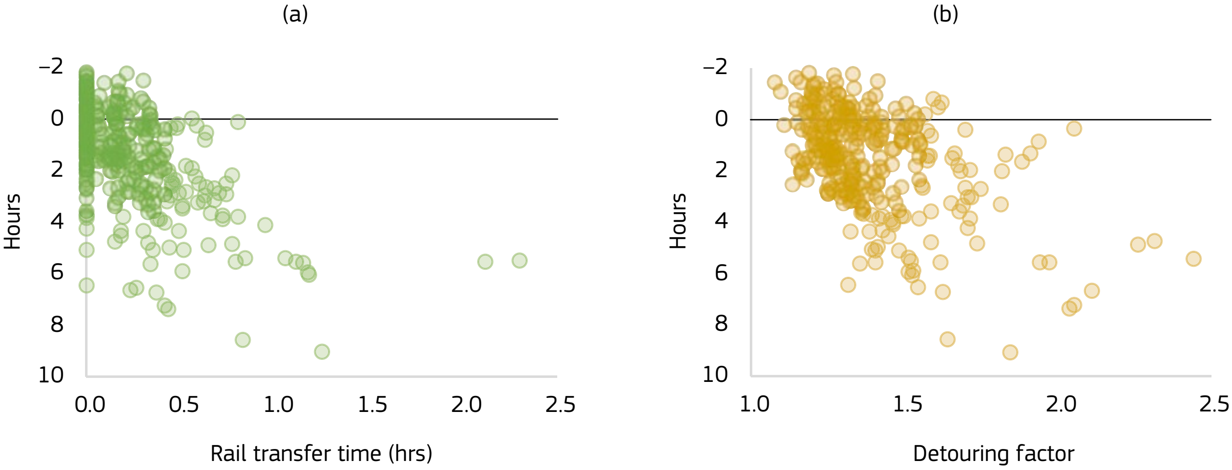
Sources: DG Regional and Urban Policy, the JRC (based on Sabre airline data).

High rail speed alone may not lead to a fast rail trip if much time is lost in between connections. In our dataset, the rail connection requires one or more transfers on two thirds of routes (Figure 6a). The total time in transfer remains below 1 hour on almost all routes, with a handful of exceptions with transfer times between 1 and 2.5 hours. As expected, rail trips are slower when transfer times are longer. On all routes where transfer time exceeds 30 minutes, the rail trip is slower than the air-based trip.

The rail distance between city pairs exceeds, by some degree, the distance 'as the crow flies'. A detouring factor can be calculated as the ratio of the rail distance to the straight-line distance. This ratio tends to be higher on routes traversing areas that contain mountain ranges, curved coastlines or estuaries. Higher values for this detouring factor are associated with higher relative travel times for rail (Figure 6b).

On cross-border routes, the rail trip tends to be slower than on domestic routes. Table 4 provides insight into some of the explanatory factors behind this. Rail operating speeds are on average 20 km/h lower on cross-border routes. The detouring factor is slightly higher, though not by much. The largest differences are seen for the transfer time, which is on average three times higher on cross-border routes than on domestic routes. This is true for both the absolute transfer time in hours and the share of the transfer time in the total rail trip.

Figure 6: Difference in travel time by rail as opposed to air according to rail transfer time and detouring factor, 2019



NB: Negative values on the vertical axis indicate that the total travel time by rail is less than that by air.

Sources: DG Regional and Urban Policy, the JRC (based on Sabre airline data).

Table 4: Rail operating speed, transfer time and the detouring factor of rail trips

	Rail operating speed (km/h)	Transfer time (h)	Transfer time (% of rail trip)	Detouring factor
Cross-border routes	117	0.36	7.6	1.42
Domestic routes	138	0.12	2.5	1.37
All routes	126	0.25	5.3	1.40

NB: Interactive versions of the maps in this paper can be accessed via the interactive viewer at: https://ec.europa.eu/regional_policy/assets/scripts/map/regio-gis-maps/public_transport/rail_vs_air.html. The viewer provides interactive maps on rail operating speed and transfer time as a share of the rail trip.

Sources: DG Regional and Urban Policy, the JRC (based on Sabre airline data).

Route distance and rail speed appear to be important determinants of the relative performance of rail trips. As seen in Section 2, rail speed in turn varies between EU regions, between cities of different population sizes and between cross-border and domestic routes. As such, these factors can be expected to have an impact on the relative performance of rail trips.

In order to investigate this in more detail, we carried out a multivariate analysis to identify the impact of these factors on the relative performance of rail trips, based on the following model specification.

$$RP_i = a + \beta_1\, Distance_i + \beta_2\, Crossborder_i + \beta_3\, Population_i + \beta_4\, North\_western_i + \beta_5\, Southern_i + \varepsilon_i \quad (1)$$

The dependent variable RP_i represents the difference between the travel time of a rail trip on route *i* and the time of an air trip. The variable has positive values if the rail trip is faster. $Distance_i$ represents the distance in kilometres of route *i*, while $Crossborder_i$ is a dummy variable indicating whether a route concerns a cross-border trip. $Population_i$ is the sum of the population in the two cities connected by the route *i*. $North\_western_i$ and $Southern_i$ are variables that account for the geographic location of the route. They have value one if a route's cities are located in the north-western or southern Member States, respectively. If only one of the two cities is located in the EU region in question, the respective value of these variables is 0.5. Finally, ε_i is a disturbance term.

Estimation results (Table 5) show that the relative performance of rail trips is negatively related to the trip distance, confirming that rail tends to have a comparative advantage over flights on shorter distance trips, owing to the relatively long out-of-vehicle time for air trips on such trips. The relative performance of rail is lower on cross-border trips than on domestic trips. This can be explained by the lower rail speed on cross-border routes, as found in the analysis of Section 2. Rail performs relatively well on routes between more populous cities, which may be linked to the larger share of high speed, or otherwise faster, rail connections between major cities. Furthermore, results show that on routes in the north-western Member States, rail trips tend to perform relatively well vis-a-vis air trips, as compared to routes in the eastern Member States. To a large extent this can be explained from the higher prevalence of high-speed and other fast rail connections in countries such as Belgium, Germany, France, Luxembourg and the Netherlands. For routes in the southern Member States no significant difference is found, despite well-developed high-speed rail networks in Spain and Italy.

Table 5: Estimation results – explaining the variation in relative rail performance

Variable	Model_1	Model_2
Distance	−.0123***	−.00924***
Crossborder	−1.28***	.226**
Population	2.82e-07***	−7.09e-08***
North_western	1.97***	.57***
Southern	.515	−.0326
Rail_speed		.0304***
Rail_transfer		−1.62***
Rail_detour		−2.93***
_cons	1.02**	1.85***
N	297	297
r2_a	.51	.911

Legend: * $p < .1$; ** $p < .05$; *** $p < .01$.

NB: Full estimation results are available in Annex B.

These estimation results and the findings in Sections 2 and 3 suggest that a large part of the impact of many of these determinant factors on the comparative advantage of rail trips appears to run via the speed of the train connection, the transfer time and the detouring factor. In order to test this, we estimated a second model in which we directly included the train speed, transfer time and detouring factor as additional variables to the model specification.

$$RP_i = a + \beta_1\, Distance_i + \beta_2\, D\_Crossborder_i + \beta_3\, Population_i + \beta_4\, D\_North\_western_i + \beta_5\, D\_Southern_i + \beta_5\, Rail\_Speed_i + \beta_5\, Transfer_i + \beta_5\, Detour_i + \varepsilon_i \quad (2)$$

$Rail\_speed_i$, $Rail\_transfer_i$ and $Rail\_detour_i$ denote the average train speed, transfer time and detouring factor on route *i*, respectively. The results show that including these variables improves the model fit and the share of variation in the dependent variable explained increases from 51 % with model (1) to 91 % with model (2). According to expectations, the coefficient of rail speed is positive, indicating that a higher speed increases the relative performance of the rail trips. The coefficients of the transfer time and detouring factor are negative, indicating that the relative performance of rail is lower when transfer times are higher and distance over the rail is higher compared to straight-line distance.

Results indicate that in terms of explaining the relative rail performance, the rail speed and route distance are the most important variables (29), followed by the detouring factor and the transfer time. When accounting for these additional factors, the impact and relative importance (30) of the cross-border variable, population variable and north-western variable all diminish. The coefficient of the cross-border variable is no longer negative, suggesting that its negative impact on rail performance runs mainly via rail speed, transfer times and/or detouring. The population variable turns negative, indicating that after accounting for the additional variables, rail has a comparative disadvantage on routes between larger cities. This can be explained from the fact that for our dataset, the distance from the city centroids to the departure rail stations tends to increase in city population size, whereas the distance to the airport remains constant. Relative rail performance remains higher in north-western Member States, after accounting for rail speed. This is related to access trips to and from airports, which tend to be longer in the north-western Member States.

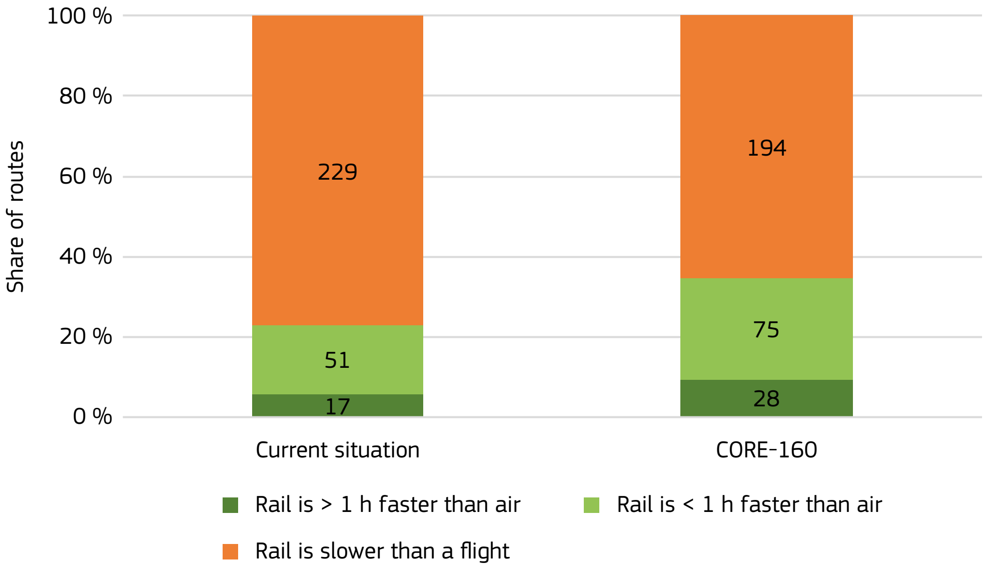
3.4. WILL INCREASED RAIL SPEEDS MAKE MORE TRIPS FASTER BY RAIL THAN BY AIR?

In December 2021, the Commission adopted a proposal (31) for the revision of the TEN-T regulation, in which the Commission proposed, among other things, a minimum speed for passenger rail on the core and extended core network of 160 km/h.

This section explores the effect of rail speed improvements on its potential to compete with short flights on travel time. It does so by means of a scenario which assumes that rail improvements lead to an increase in operating speed to 160 km/h on the TEN-T core network (CORE-160) (32).

The speed improvements of CORE-160 result in a decrease in the rail travel time on 249 of the 297 routes. On 35 of these routes, the rail trip is now faster than the air trip (Map 4), increasing the total of such routes from 68 to 103 routes (Figure 7). The number of routes where rail is more than 1 hour faster increases from 17 to 28 in this scenario.

Figure 7: Difference in travel time between a rail and an air trip, 2019



Sources: DG Regional and Urban Policy, the JRC (based on Sabre airline data).

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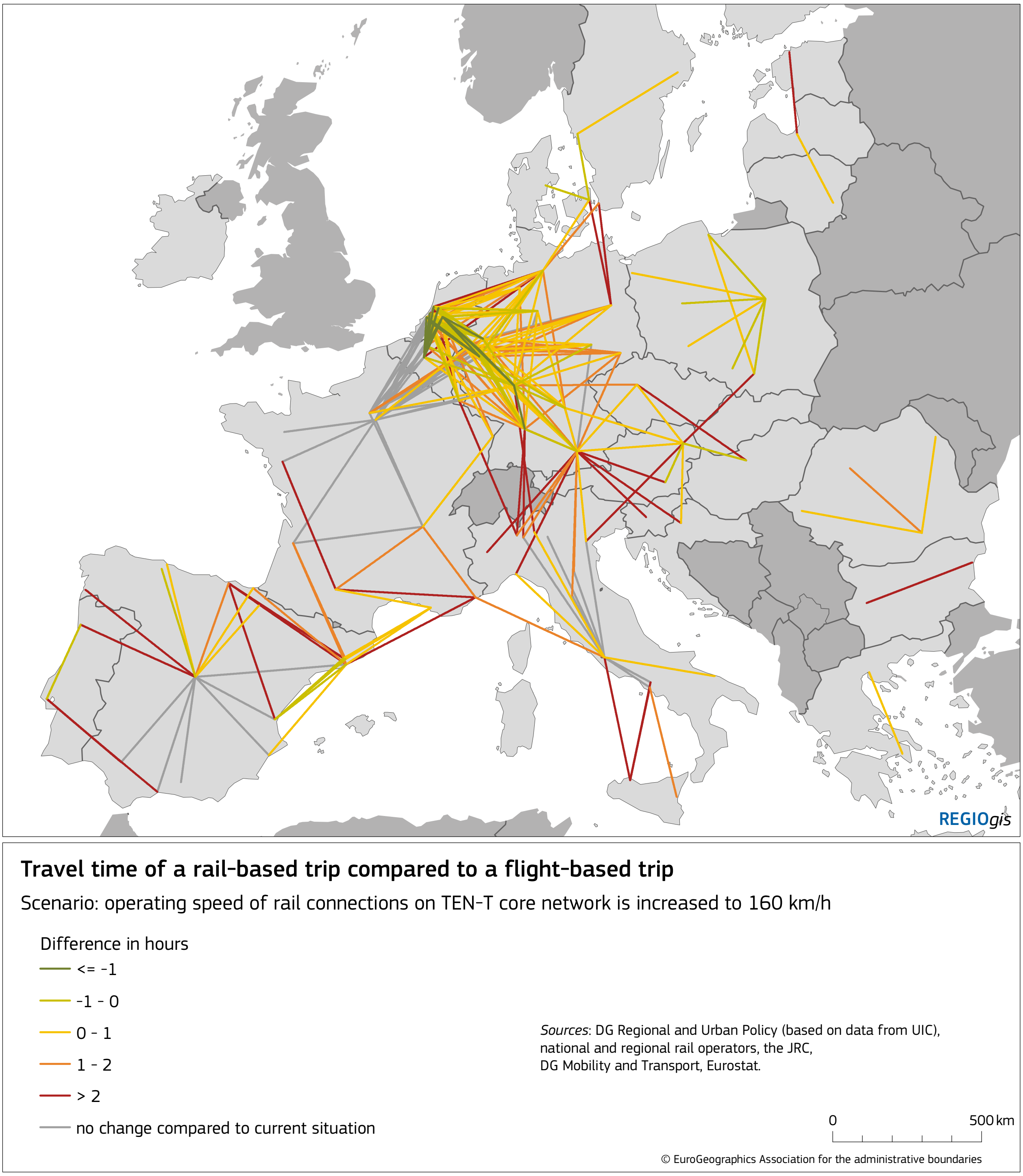
(29) As measured by the standardised beta coefficients.

(30) As measured by the β coefficients and the standardised beta coefficients, respectively (see also Annex B).

(31) European Commission (2021).

(32) Annex A provides details about the methodology used to calculate the TEN-T rail network length per route.

Map 4: Travel time of a rail-based trip compared to a flight-based trip in scenario CORE-160, 2019 (33)



Sources: DG Regional and Urban Policy (based on data from UIC), national and regional rail operators, the JRC, DG Mobility and Transport, Eurostat.

© EuroGeographics Association for the administrative boundaries

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(33) Interactive versions of the maps in this paper can be accessed via the interactive viewer at: https://ec.europa.eu/regional_policy/assets/scripts/map/regio-gis-maps/public_transport/rail_vs_air.html. The viewer provides additional information and visualisations per map, along with additional maps on related topics.

3.5. WOULD A SWITCH TO RAIL REDUCE CO_2 EMISSIONS AND SAVE TRAVEL TIME?

The fact that on 68 out of 297 routes a rail trip is currently faster than an air trip signifies that there is potential for a modal switch. If passengers on those routes were to switch from using an airplane to using a train, this would not only lead to a reduction in CO_2 emissions (and other environmental costs) but would also result in travel time savings.

Calculation of CO_2 emissions

Aviation

Data on fuel consumption by aircraft are taken from Annex 5 of the *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019*. We follow Avogadro et al. (2021) in calculating emissions as the average emission levels of the two most employed aircraft models used for intra-European flights (i.e. the Airbus 318 and Boeing 737 aircraft). For the landing-take-off cycle, fuel consumption is 685 kg for an Airbus 318 and 825 kg for a Boeing 737. We calculate the fuel consumption of the cruise-climb-descent cycle by inter- and extrapolation from a sample of fuel consumption for flight distances within the range of 125 – 250 nautical miles (232 – 463 km) provided in the annex. For an Airbus 318 aircraft this yields a fixed fuel consumption component of 197 kg and a variable component of 2.9 kg/km. For a Boeing 737 aircraft these values are 202 kg and 3.0 kg/km, respectively. The amount of CO_2 emissions from one kg of fuel is 3 150 grams. For the flights in our dataset, the levels of CO_2 emissions are thus calculated to consist of a fixed component of 3 007 kg plus a distance-related component of 9.3 kg/km.

Rail

Data on CO_2 emissions for rail are derived from Prussi and Lonza (2018), which calculate high-speed rail emission profiles for various routes between city pairs in Europe and the United Kingdom, with distances ranging between 480 and 800 km. The average value across these routes is 23 grams of CO_2 per passenger kilometre.

This section provides an analysis that starts with the supposition that air passengers indeed switch to rail whenever a rail trip provides a shorter travel time (34). The implicit assumption could be that rail improvements on these routes have been carried out to the extent that passengers are now indifferent between an air-based and a rail trip, apart from the difference in travel time (35). The analysis quantifies the impact such a modal switch would have on CO_2 emissions (36) (37) and on total travel time.

In our dataset, the aforementioned modal switch would result in a decrease in passengers by 21 % (Table 6). Total CO_2 emissions on these routes would decrease by 17 %. The impact on CO_2 emissions is lower than the impact on the number of flights, reflecting the fact that the modal switch takes place disproportionally on shorter short-distance flights, where total fuel consumption is lower (38). Furthermore, part of the reduction in CO_2 emissions from flights is replaced by emissions from additional rail trips (39). As passengers switch to a faster

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(34) The input data used for this analysis do not distinguish between point-to-point air passengers (those for which the city pair in question forms the origin and destination of their trip) and connecting passengers (those for which the route in question forms only one leg of their flight trip). The latter are less likely to switch to rail, even if it provides a faster connection between city centres. Hence, the number of modal switches derived from this supposition represents an upper range.

(35) Economic theory states that rational passengers will select the mode that provides them the highest utility, which can be seen as an indicator that reflects all costs and benefits associated with using the mode in question. These do not only include travel time but also ticket costs, reliability, comfort, safety and various other aspects that matter to the passenger. Furthermore, preferences are heterogeneous, meaning that the utility of a specific mode can differ between individuals. This explains why it is not always the fastest mode that is chosen and why not all passengers choose the same mode. Passengers can be incentivised to switch to rail by market-based mechanisms such as CO_2 taxation and rail fares subsidisation, or via investment policies aimed at improving operating speed, rail connections and station accessibility. Ultimately, these measures lead to a modal switch by improving the utility of rail vis-à-vis that of flights. Unfortunately, we do not have information on the current level of these utility components (apart from travel time), nor do we have information on the passengers' sensitivity to changes in these components. Furthermore, we do not have information on the current modal split. This prevents us from carrying out an analysis based on modal choice theory.

(36) The analysis focuses on CO_2 emissions from a rail trip or flight. It does not take into account CO_2 emissions from trips between the city centres and the rail station / airport. It does not take a full life-cycle approach, and as such does not take into account CO_2 emissions related to rail investments.

(37) This analysis does not account for the potential changes following the entry into force of the new legislative proposal for a harmonised framework for greenhouse gas emissions accounting in freight and passengers transport segments, in brief 'CountEmissions EU' (European Commission, 2020). This initiative is action 33 of the action plan of the sustainable and smart mobility strategy.

(38) Note, however, that for short-distance flights the per km CO_2 emission reductions are higher.

(39) On average, across all routes in our dataset, CO_2 emissions from a rail trip are about 6.5 times lower than emissions from a flight.

alternative, total travel time is expected to decrease. Total travel time savings on the 297 routes are 4.2 %.

Table 6: The impact of a modal switch to faster rail connections on passengers, CO_2 emissions and the passenger travel time, 2019

	Current situation	CORE-160
Number of air passengers	–21.1 %	–30.5 %
CO_2 emissions	–16.7 %	–25.0 %
Travel time	–4.2 %	–6.1 %

NB: The values in the table show the change in the number of passengers, CO_2 emissions and travel time of all air trips on the 297 routes analysed.

Sources: DG Regional and Urban Policy, the JRC (based on Sabre airline data).

The potential of rail to compete with flights increases substantially in the CORE-160 scenario discussed above, in which the operating speed is improved. Since the number of routes where rail outperforms flights increases, the potential modal switch also increases, leading to larger reductions in CO_2 emissions and total travel time.

In the CORE-160 scenario, a modal switch to rail whenever it is faster would result in a decrease in the number of passengers by 31 % (Table 6). The decrease in passengers results in further reductions of CO_2 emissions. CO_2 emissions from air trips would decrease by 25 % in the CORE-160 scenario. Due to increased speed, total travel time savings on the routes analysed would be larger in the speed improvement scenario, compared to the current situation. In CORE-160 the total travel time would be lower by 6.1 %.

4. CONCLUSIONS

Travelling by rail between medium and large EU cities located less than 500 km apart is rarely fast and often slow. Of these 1 356 routes, only 3 % have straight-line rail speeds that exceed 150 km/h and 30 % have speeds below 60 km/h. Rail speeds tend to be especially low in eastern Member States and on cross-border routes.

The paper then zooms in on 297 routes between EU cities that are served by both rail and a direct flight. Comparing the travel time between the city centres by air and by rail shows that for around a quarter of the routes (68) the rail trip is faster. On 17 routes, the travel time savings by rail even exceeds an hour. Trip distance and train operating speed have the biggest impact on the travel time by rail. For shorter trips, rail can often offer a faster connection, while for longer trips a high speed is required.

More of the time is spent on the train during a rail trip in comparison to a flight, where often most of the time is spent getting to and from the airport and in a queue. Therefore, improving rail operating speed has the biggest impact on travel times. Reducing transfer times between trains, however, can also significantly reduce travel time.

The proposed rail speed for the TEN-T core network would increase the number of routes where rail trips are faster than air trips from 68 routes to 103 routes. If air passengers were to switch to using a train on routes where the rail trip is faster, CO_2 emissions and travel time would be reduced. Our estimates indicate that such a switch would reduce CO_2 emissions from air trips on these 297 routes by 17 % and decrease travel time by 4.2 %. Improved rail speeds on the core TEN-T network would increase the impact of such a switch. CO_2 emissions would decrease by 25 % and travel time by 6.1 %. Such a switch would, however, require improvements beyond travel time, including cost, convenience, frequency and flexibility. It may also require investment in rail capacity on specific routes.

Improvements could focus on cross-border connections, where rail operating speeds tend to be lower and transfer times longer than on domestic routes. The same goes for routes in eastern Member States where the train speeds are lower than in other parts of the EU and the number of missing connections is higher.

In north-western and southern Member States, almost all cities are connected and rail trips tend to be somewhat faster. Nevertheless, for routes with many air passengers, rail operating speeds are still too low to offer an appealing alternative. Improving such connections could persuade more people to take the train and thus reduce the pressure on the airports servicing these busy routes.

ANNEX A – METHODOLOGY

SELECTION OF LINKS BETWEEN MAJOR URBAN CENTRES

This analysis considers links between major urban centres (40) that are located within a maximum of 500 km from each other. Only urban centres that have a population of at least 200 000 inhabitants or are a capital city were taken into account. A straight-line distance matrix between the centroid points (41) of all selected urban centres was calculated. From this matrix, only pairs of urban centres located within 500 km from each other were selected (42).

SELECTION OF AIRPORTS BETWEEN WHICH SHORT FLIGHTS OPERATE

Eurostat provided data on the number of flights and passengers relative to the first leg of flights departing from European airports. The data refer to the year 2019 and are organised by a pair of airport codes (origin/destination). The dataset does not contain any distinction between regular scheduled flights or general aviation flights (i.e. private business or recreational flights). The data on flights and passengers are matched with the point location of the airports, which allows the straight-line (geodesic) distance between the airports to be calculated.

From all airport connections, those that had a straight-line distance of less than 1 000 km were selected. Many of the selected connections only represented a small number of flights and/or passengers. For the analysis in Section 4, only connections with at least 365 flights per year and at least 36 500 passengers per year (by direction) were selected in order to focus on the main connections and avoid less important flights to unduly affect the results.

WHICH SHORT FLIGHTS ARE RELEVANT FOR WHICH URBAN CENTRES?

To assess air connectivity between urban centres, the spatial relationship between airports and urban centres needs to be examined. For all airports where the selected flights operate, the straight-line distance to the centroid points of the urban centres was calculated. Finally, for each airport, all urban centres that are located within less than 40 km from the airport were selected (43). This resulted in a table providing a many-to-many relationship between urban centres and nearby airports.

LINKING SHORT FLIGHTS TO PAIRS OF URBAN CENTRES

Using the selection of urban centre pairs, a specific set of short flight connections can be established: short flight connections between airports that provide a link between urban centres that are located within 500 km from each other. This means that the airports themselves can be located within more than 500 km from each other. For each of these airport connections, the number of flights and passengers per day and per direction was registered.

The data on the available air connections could now be transferred to pairs of urban centres. Some of the urban centre pairs are connected by more than one air connection (44). Therefore, if multiple air connections were available for a single urban centre pair, the connection representing the highest number of passengers was selected for further analysis of travel time between urban centres.

HOW ARE AIRPORTS CONNECTED TO NEARBY URBAN CENTRES?

The list of flight connections between selected urban centres was used to assess travel times between the airports and the urban centres nearby. Using a comprehensive road network, the travel time by car between the airport and the urban centre centroid was calculated. The calculation used the speed parameters provided with the road network dataset and did not take congestion into account. Alternatively, travel time by public transport between the city centre and the airport could have been calculated. Unfortunately, this option is currently not available for all major cities, because of the lack of comprehensive machine-readable public transport timetables (45).

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(40) An urban centre is a cluster of contiguous 1 km² grid cells with a population density of at least 1 500 inhabitants per km² and collectively a population of at least 50 000 inhabitants. See Eurostat (2019), p. 30, for more details.

(41) Each urban centre is represented by its population-weighted centroid point. The location of this point is calculated using the 1 km² population grid that determines the urban centre definition.

(42) Because of the importance of rail and air connections, the urban centre pair Madrid–Barcelona (with a straight-line distance of 508 km) was also taken into account.

(43) In exceptional cases, a few major urban centres located slightly further away than 40 km were also taken into account: for instance The Hague, at 41.6 km from Schiphol.

(44) For instance, Amsterdam and Paris are linked by two air connections (from Schiphol to Paris Charles de Gaulle and to Paris Orly).

(45) Suitable timetable datasets are available for about half of the number of selected urban centres and their surroundings.

ESTIMATING TOTAL AIR TRAVEL TIME BETWEEN URBAN CENTRES

Using all previous selections, the total travel time by air between urban centres was estimated as the sum of the following components.

- Travel time by car from the city centre of departure to the airport.
- Time at the airport before the flight (check-in, transfers inside the airport, boarding): 1 hour.
- In-vehicle time: time on the aircraft, based on real-time flight schedule data from Sabre. This is assumed to include the taxiing time.
- Time at the destination airport (leaving the aircraft, transfers inside the airport): 30 minutes.
- Travel time by car from the arrival airport to the centre of the destination city.

SELECTION OF RAIL STATIONS WITHIN URBAN CENTRES

All stations located in major urban centres were selected from a dataset of point locations of rail stations for which passenger rail timetables are available. For some urban centres this led to a list of several dozens of stations. Many of these may have been stops of local importance that were not relevant when assessing the best available rail trips to other major urban centres. Using all possible pairs of stations located in the selected pairs of urban centres would have led to an excessive amount of origin/destination calculations to be performed. For that reason, only the major stations in each of the urban centres were selected. First, we computed the total number of departures per station, observed during a weekday between 6:00 and 20:00. From the timetable dataset we also derived the maximum length of direct trips starting from the station. If this maximum length is very low, this gives an indication that only local trains operate at that station. Consequently, we applied a qualitative selection of major stations in cities with more than 10 stations, guided by the variety in numbers of departures by station, by the maximum length of direct trips starting at the station and by the names of the stations (46).

CALCULATING RAIL TRAVEL TIME BETWEEN MAJOR STATIONS

The best available rail connection between selected urban centres may depend on the choice of departure and arrival stations, and on the moment of departure. This means that origin/destination calculations are needed to compute the shortest available travel time for each pair of stations representing a pair of urban centres, and that this computation needs to be performed several times to capture possible differences in travel time during the day. Using OpenTripPlanner Analyst, the best available travel time was calculated for the preferred departure, each quarter of an hour between 4:00 and 23:45 on a weekday in 2019. These results were aggregated for each pair of urban centres by selecting the shortest travel time observed during the day, between any pair of stations providing a connection between the urban centres. The location of the stations between which the shortest travel time was observed was known, which means that the straight-line speed of the trip could also be calculated. OpenTripPlanner searches for trips of a maximum of 10 hours. If a city pair cannot be connected within 10 hours travel time, that city pair is considered not to be connected by rail.

The OpenTripPlanner Analyst software allows many parameters to be used. Changing these parameters influences the results. The following parameters were set:

maxWalkDistance = 900 (m)
maxTransferWalkDistance = 900 (m)
walkSpeed = 1.33 (m/s)
walkReluctance = 2.0 (= default)
waitReluctance = 1.0 (= default)
waitAtBeginningFactor = 0.4 (= default)
transferSlack = 300
maxTransfers = 5
maxTimeSec = 36 000
clampInitialWait = –1 (= default)
dominanceFunction = EarliestArrival
transit modes = RAIL, SUBWAY, WALK

CALCULATING THE TEN-T RAIL NETWORK LENGTH BETWEEN URBAN CENTRES

We examined how each of the rail connections between selected urban centres relates to the TEN-T passenger rail network.

The centroid points of the urban centres were used as input data, combined with the geodata of the TEN-T core and comprehensive passenger rail networks.

The process involved the following steps.

1. The centroid points of the urban centres were snapped (47) to the TEN-T core network. If a TEN-T core link between the centroids of both urban centres was found, its network length was registered.
2. The centroid points of the urban centres were snapped to the TEN-T comprehensive network. If a TEN-T

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(46) For instance, stations with well-known names were selected, and stations with a name containing certain keywords (in particular *Hbf* (abbreviation for ‘central station’) in German).

(47) For the purpose of the analysis the centroid point is moved to the nearest point on the TEN-T network. This process is required to allow for the calculation of rail network routes between the urban centres.

comprehensive network link between two urban centres was found, its network length was registered.

3. The network length(s) found in steps 1 and 2 were compared to the straight-line distance between the urban centre centroids. An excessive network length in comparison with the straight-line length of the connection indicates a potential routing problem. The potentially problematic cases were inspected in a tabular and a cartographic way. It appears that, in most cases, a network length that is no longer than 2.5 times the straight-line distance can be considered as a plausible result. This maximum factor allows for the presence of network detours that are required because of geographic obstacles such as mountain ranges, curved coastlines and estuaries.
4. If both a TEN-T core route and a TEN-T comprehensive route were found, the TEN-T core route would be taken into account provided that its length did not exceed the straight-line distance by 2.5 times. If that condition was not met, the TEN-T comprehensive route would be taken into account, provided that its length did not exceed the straight-line distance by 2.5 times. The speed on the selected TEN-T network route was calculated by dividing the route length by the travel time. Note that this travel time may have included transfer times if no direct train connection was available.
5. The connections were ranked by TEN-T network speed to detect possible outliers. Specific problem cases were inspected and corrected where possible. In particular, some connections appeared to operate at a suspiciously high speed. This was due to routing detours calculated by the network analyst tool. Such routing detours are often caused by topological errors in the TEN-T geodata (in particular small gaps between network segments). In such cases, the length of a more direct route, preferring TEN-T core network segments where possible, was calculated by summing the length of all necessary network segments.

Consequently, although several plausibility checks were applied, it could not be guaranteed that the network length of the connections and the related speed values were always 100 % correct. The available TEN-T network geodata were not entirely suitable for routing purposes. In addition, there may have been various alternative paths connecting two urban centres. In those cases, only detailed knowledge about the actual railway segments used would have allowed a precise network length of the connection to be calculated.

ESTIMATING TOTAL RAIL TRAVEL TIME BETWEEN URBAN CENTRES

Using the comprehensive road network, the travel time by car between the centroids of the urban centres and the departure and arrival stations was calculated. The total travel time by rail between urban centres was estimated as the sum of the following components.

- Travel time by car from the city centre to the departure station.
- Time at the departure station (transfer time before boarding): 15 minutes.
- Optimal rail travel time (best available travel time during the day).
- Travel time by car from the arrival station to the centre of the destination city.

ANNEX B – DETAILED ECONOMETRIC RESULTS

Table 7: Estimation results of model (1)

Source	SS	df	MS
Model	622.008629	5	124.401726
Residual	577.60733	291	1.98490492
Total	1199.61596	296	4.05275662

Number of obs	=	297
F(5, 291)	=	62.67
Prob > F	=	0.0000
R-squared	=	0.5185
Adj R-squared	=	0.5102
Root MSE	=	1.4089

Difference	Coef.	Std. Err.	t	P>|t|	Beta
Distance	–.0122736	.0008066	–15.22	0.000	–.6396945
Crossborder	–1.282027	.1850334	–6.93	0.000	–.3169762
Population	2.82e-07	3.78e-08	7.46	0.000	.3103763
North_western	1.972918	.3586147	5.50	0.000	.3989693
Southern	.5150147	.4067827	1.27	0.207	.0918812
_cons	1.019371	.4429961	2.30	0.022	.

Table 8: Estimation results of model (2)

Source	SS	df	MS
Model	1095.60309	8	136.950387
Residual	104.012866	288	.361155784
Total	1199.61596	296	4.05275662

Number of obs	=	297
F(8, 288)	=	379.20
Prob > F	=	0.0000
R-squared	=	0.9133
Adj R-squared	=	0.9109
Root MSE	=	.60096

Difference	Coef.	Std. Err.	t	P>|t|	Beta
Distance	–.0092404	.0003641	–25.38	0.000	–.4816073
Crossborder	.2255687	.0919938	2.45	0.015	.055771
Population	–7.09e-08	1.95e-08	–3.64	0.000	–.0780111
North_western	.5699573	.1586595	3.59	0.000	.1152585
Southern	–.0326249	.1768106	–0.18	0.854	–.0058205
Rail_speed	.0303573	.0011677	26.00	0.000	.5693783
Rail_transfer	–1.6162	.143999	–11.22	0.000	–.2423063
Rail_detour	–2.934947	.1782464	–16.47	0.000	–.304353
_cons	1.854503	.3195	5.80	0.000	.

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