Air2Rail

Reducing CO_2 from intra-European aviation by a modal shift from air to rail

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Koios strategy

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Management summary

The contribution of global aviation to climate change is projected to triple by 2050. This is clearly incompatible with the Paris Agreement. One way to curb this development, is to make people take the train instead of the plane. Travel by aviation within Europe,[1] emits on average 5 to 6 times more CO_2 per passenger-kilometre than by train. To reduce the growth in intra-European aviation, improvements in the speed and quality of rail services are considered and implemented. The present study estimates the potential reduction in CO_2 from intra-European aviation, by a modal shift to rail.

The potential CO_2 reduction is estimated for three assumed railway improvements:
- All railway services competing with aviation, have the modal split of the contemporary best high-speed rail connections. This implies HSR between all larger cities in Europe.
- All railway services competing with aviation become 10% faster.
- The number of intra-European night trains is increased by 50%.

The present study did not investigate measures and costs required for these improvements in rail services.

The overall conclusion from this study is that 4 to 7 Mt CO_2 from intra-European aviation may be avoided by a modal shift from aviation to railways. This corresponds with 6% to 11% of the CO_2 emissions from intra-European aviation and with 2% to 4% of CO_2 from all fuel bunkers in Europe, which includes departing intercontinental flights. To achieve this reduction in CO_2, faster intra-European rail services are required, in combination with policies which discourage flying. Train travel in Europe on distances between 200 and 1000 km needs to increase by around 50% in 2040. This includes the new passengers coming over from aviation plus the trend-wise growth of 1% per year.

The main recommendation for the railway industry is to develop a truly European strategy and marketing. Governments need to implement policies which discourage flying. When considering public funding for railway improvements, the dynamics and environmental impact in the entire intra-European travel market need to be assessed. Travellers are advised to take the train instead of the plane, whenever possible.

[1] Europe comprises in this study the EU-28 plus Switzerland, Norway and Iceland. The United Kingdom was still member of the EU during most part of the present research.

1. Introduction and acknowledgements

The growing contribution of aviation to climate change is a grave concern. One mitigation solution is to make people shift trips from aviation to railways. The CO_2 emissions per passenger-kilometre from rail are, indeed, much lower than from air. Train travel on distances from 200 to 1000 km – European scale – can be an alternative to flying. The present study estimates the potential reduction in CO_2 from intra-European aviation, by a modal shift to rail.

An important backbone for this study is a detailed database of the intra-European aviation market, including the related CO_2 emissions. T&E developed this database in conjunction with the present study. Annexes A and B describe the crucial contribution of Juliette Egal and Thomas Earl, both from T&E. I thank them for their great effort and the fruitful exchange of information and ideas we had.

Furthermore, I thank Dimitrios Papaioannou from the International Transport Forum and Barth Donners from RHDHV for their willingness to share data from their respective intercity travel models with me and for answering my questions.

Finally, I am grateful to T&E, for giving me the opportunity to investigate the potential environmental benefits of a modal shift from aviation to rail. However, the views expressed in this report are not necessarily supported by T&E and are solely my responsibility.

2. Aim and research method

Aim of this study is:

To estimate the potential reduction in CO_2 from intra-European aviation, by a modal shift from air travel to railways

To gain the desired insight, information is required on these three topics:
- The intra-European aviation market, with the related CO_2 emissions (chapter 4).
- The intra-European rail market on distances competing with aviation, including the CO_2 emissions (chapter 6).
- The determinants for people to choose rail over air travel, or the other way around (chapter 5).

Detailed information about the number of people traveling between airports in Europe, is available from Eurostat (2019). These statistics form the basis of T&E's 'European Aviation CO_2 database' (Annex A). If a city has more than one airport, these airports are combined, resulting in passenger volumes between city pairs. This being relevant for the competition with rail.
CO_2 emissions per flight between specific airports and types of aircraft are derived from Plane Finder and the ICAO CO_2 Calculator Methodology.[2] The combination of these data sources, results in a database which can be used to gain insight in the passenger volumes and CO_2 emissions between specific city pairs, for different distance classes and for passenger volume classes. The following chapters will use results obtained from this database.

Data on the intra-European rail market are, unfortunately, not available. Most railway companies regard information about passenger volumes between city pairs, as business confidential. Through a mix of sources, data are acquired on 34 city pairs (Annex B). To arrive at an estimate of the entire rail market at distances between 200 and 1000 km, several statistics are combined. Eurostat data on all intra-European rail passenger kilometres are taken as starting point (EC 2019). Subtracted from this is the share of urban and regional rail – for which aviation is not an alternative – based on model estimates by the International Transport Forum (ITF 2020). Finally, a linear diminution of the passenger volume by rail is assumed between 200 and 1000 km.
The CO_2 emissions per passenger-kilometre depend on train type, speed, occupancy and the CO_2 from the electricity generation, which differs between countries. The present study doesn't take these differences into account and uses only a European average value of 0.025 kg CO_2 per passenger-kilometre for train travel.[3]

Two existing models of the intra-European passenger market have been considered as estimate for the rail market (ITF 2020; RHDHV 2020). These models contain calculated estimates of the travel volumes per mode and between different cities. Both models are not based on empirical data of passenger volumes between city pairs. Comparing the calculated air travel volumes, with the data from Eurostat, however, shows large differences. Therefore, these models are not used in the present study as representation of the European passenger market. However, some specific uses are made from calculations with these models.

The determinants for the choice people make between air and rail travel, are derived from the international literature, including available empirical evidence (chapter 5).

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[2] See Annex A for details.

[3] Somewhat below the 28.39 g CO_2/pkm, being the last available official figure published by the European Environmental Agency over 2014 (EEA 2017). Emissions for specific trips by different modes, can be estimated with the EcoPassenger tool from the UIC.

The chapters 4 and 6 on the European travel market and 5 on determinants for mode choice, are the main building blocks for the assessment of the potential CO_2 reduction in chapter 7. Because this is a static analysis with mainly 2017 data, relevant dynamics in the European travel market are reviewed in chapter 8. The closing chapter 9 presents the main conclusions and recommendations. First, a brief overview is sketched of the climate impact from aviation.

3. Climate impact from aviation

CO_2 emitted by worldwide commercial aviation is estimated at 918 million-tonnes (Mt) CO_2 in 2018 (ICCT 2019). This corresponds with 2.4% of global emissions. However, aviation is growing fast and its CO_2 emissions have grown by 5.7% a year since 2013. This growth is stronger than the projections by ICAO, the UN organization for civil aviation. ICAO's baseline projects an annual growth rate of 3.8% in CO_2 emissions until 2050 (ICAO 2019). Even this lower-than-actual growth, will more than triple the emissions, resulting in around 1,900 Mt in 2050. In that same year, global emissions from all sectors together need to be reduced to below 3,000 Mt CO_2, in accordance with the Paris Agreement (IPCC 2019). So, under ICAO's baseline projection, aviation's share will rise to two thirds of the required emissions level. ICAO also sketches an alternative scenario with additional measures to reduce energy use and partly shift to sustainable fuels. This can lower the emissions from commercial aviation to 900 Mt CO_2 in 2050, which is still far too high. The CO_2 emissions from aviation need to go down to zero, not far beyond 2050, to be in line with the Paris Agreement.

The International Transport Forum developed scenarios for the growth in CO_2 from global aviation until 2050 (ITF 2019). The results of the Current Ambition and High Ambition scenarios are summarized in table 1. The Current Ambition scenario includes a CO_2 price of 100 USD per tonne, a low share of low-cost carriers on long-haul flights and building all planned high-speed rail links. These scenario assumptions are not yet current policy. The projected CO_2 emission of more than 1,000 Mt in 2050 are in line with ICAO's ambitious scenario. Improved energy efficiency of aircraft and operations contribute most to achieve this modest growth in emissions. Even the High Ambition scenario – with a carbon price of 500 USD –, doesn't reduce emissions far enough. Therefore, the ITF explores also disruptive scenarios, with e.g. electric aircraft for distances below 1600 km and a substantial use of zero-carbon synthetic fuels.

	2015	**2030**		**2050**	
		Current Ambition	High Ambition	Current Ambition	High Ambition
Billion pkm	6,967	13,533	11,091	21,977	15,861
Mt CO_2	714	995	656	1,062	399
Kg CO_2/pkm	0.103	0.074	0.059	0.048	0.025

Table 1: Two projections of the global aviation CO_2 emissions in 2030 and 2050 (ITF 2019).

The impact of aviation on climate change is not limited to its CO_2 emissions. Climate relevant emissions include nitrogen oxides (NO_x), sulphur oxide (SO_2), water vapor (H_2O), aerosols, contrails and contrail cirrus. The total climate impact of aviation is estimated to be two to four times higher than the effect of CO_2 emissions alone (IPCC 1999). However, the uncertainties concerning the impact of some of these non-CO_2 emissions are still large. Recent research indicates that the non-CO_2 impact from aviation differs strongly between routes and can be partly mitigated by changes in flight path and altitude (Scheelhaase 2019). The present report does not deal with the non-CO_2 impact from aviation.

This short review underlines that aviation needs to drastically lower its contribution to climate change. A range of options is available to achieve this:
- Continued technical improvements in aircraft and engines, to reduce energy consumption.
- Improvements in Air Traffic Management and infrastructure use, also to reduce energy consumption.
- Development and deployment of (hybrid) electric aircrafts, to reduce both the CO_2 and non-CO_2 impact from aviation.

- Use of advanced biokerosene, reducing the net CO_2 emissions.
- Use of zero-CO_2 synthetic kerosene.
- Reduced growth in air travel, through a shift toward train trips.
- Reduced growth in air travel through internalisation of external costs.
- Reduced growth in long distance travel in general.

From this range of options to reduce CO_2 emissions from aviation, the present study only focuses on the potential modal shift from air to rail within Europe.

4. CO_2 emissions from European aviation

European aviation[4] emitted 184 Mt CO_2 in 2017 (UNFCCC 2017). This includes all jet fuel taken on board in these 31 European countries, both for domestic and international flights (bunkers). So, Europe is responsible for about one fifth of the global aviation emissions. Figure 1 below shows the growth since 1990 in CO_2 emissions from commercial aviation in EU-28.

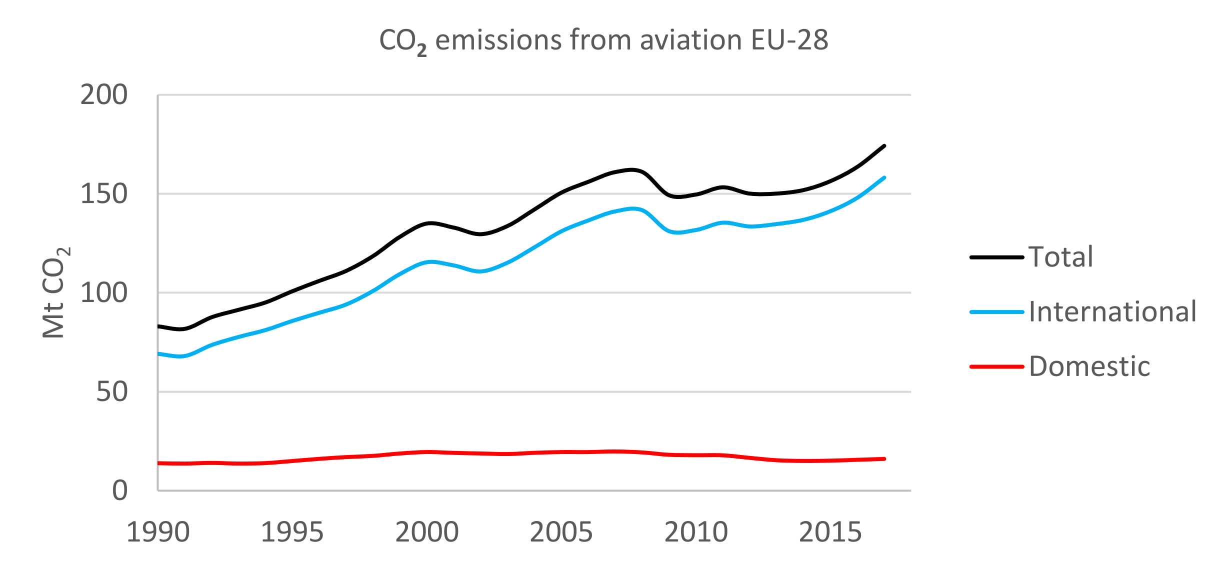

Figure 1: CO_2 emissions from European commercial aviation 1990-2017 (UNFCCC 2017).

Domestic flights – within a single country – emitted 16 Mt CO_2 in 2017, corresponding with 9% of the EU-28 total from aviation. A few countries account for the largest share of domestic emissions, due to their large size, being an island or difficult to access by surface transport (road and rail). Table 2 gives an overview of the countries with domestic aviation emissions larger than 1 MT CO_2. These countries have a substantial scope to reduce aviation emission with national policies.

Country	**Mt CO_2**
France	5.0
Spain	2.8
Italy	2.2
Germany	2.1
United Kingdom	1.8
Norway	1.1
Total top 6 countries	15.1
Total EUR-31	17.6

Table 2: CO_2 emissions from domestic aviation of countries with more than 1 Mt in 2017 (UNFCCC 2017).

[4] Europe comprises in this study the EU-28 plus Switzerland, Norway and Iceland. This demarcation is chosen because of data availability and political and geographic consistency. EUR-31 will be used as an acronym. Flights to the so-called outermost regions of the EU are not included in the present study on intra-European travel. Outermost regions include the Canary Islands, Madeira, the Azores and six French overseas territories. CO_2 from flights between EUR-31 and the outermost regions are estimated at 9 Mt.

Another way to look at the country data, is comparing aviation CO_2 per person. High scores can be caused by a high GDP/capita, being an island, difficult accessible for surface transport and having a large transfer hub for international passengers. Table 3 shows the top-ranking countries.

Country	**tonne CO_2/cap**
Iceland	3.5
Luxembourg	2.9
Cyprus	1.2
Malta	0.9
Netherlands	0.7
Switzerland	0.6
Ireland	0.6
United Kingdom	0.6
EUR-31 average	0.5

Table 3: Countries with aviation CO_2 larger than 0.6 tonne per capita in 2017 (calculated from UNFCCC 2017 and Eurostat population data).

The future growth of the CO_2 emissions from European aviation, depends on the projected growth in transport volume and expected technical improvements. Figure 2 shows projected CO_2 emissions till 2040 for six scenarios: three for passenger volume and two for technical progress (EU 2019).

Figure 2: Projected CO_2 emission from European aviation in Mt till 2040 (EU 2019).

The present report will further be limited to emissions from intra-European flights, because there lies the main potential for a modal shift from air to rail. T&E's European Aviation database calculates the emissions from intra-European flights at 62 Mt CO_2.[5] So, the remaining 122 Mt of the European aviation emissions will not be dealt with in this report, because these are related to flights between EUR-31 and countries in the rest of the world.

[5] See Annex A. Because the database uses statistics which only cover 'main airports', 8.3% of the passengers and 9.9% of the CO_2 are not included in the analyses with the database in this report. This relates to small travel volumes between some airports.

This demarcation to intra-EUR-31 flights, corresponds largely with the share of aviation covered by the European Trading System (ETS) for CO_2 allowances. Of the countries covered in the present study, only Switzerland is not participating in the ETS.

Figure 3 presents an overview of the share of CO_2 from intra-European flights per distance class. Flight distance has a large impact on the modal split between air and rail.[6] Up to a distance of 200 to 300 km, the contribution from aviation to climate change is very small. The reason is, of course, that the number of passengers flying on these short distances is small, because cars, trains and buses typically offer a faster and more frequent alternative. After a peak at distances around 500 km, the share per 100 km class, only slightly decreases.[7]

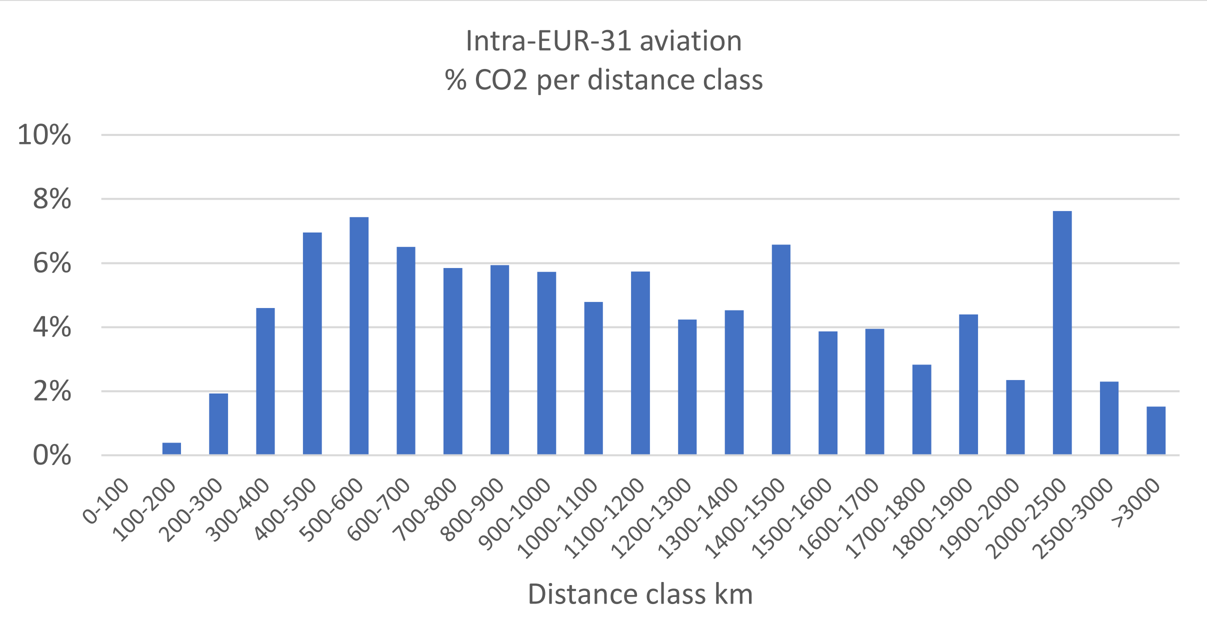

Figure 3: CO_2 share per distance class for intra-EUR-31 flights (calculated from database Annex A).

The CO_2 emissions per passenger-kilometre are also related to flight distance. The emissions during landing and take-off (LTO-cycle) weigh heavier on short flights than on long ones. Aircraft type and occupancy too, have a large impact on specific emissions. Figure 4 shows the average CO_2/pkm, depending on distance, as derived from T&E's database. The real emissions from a specific flight can differ greatly from the average, especially for short flights and for city pairs with few passengers. When comparing these specific emissions with train or car travel, it should be considered that the global warming impact from aviation is two to four times larger than from its CO_2 emissions alone.[8]

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[6] See chapter 5.

[7] Note that these data refer to intra-EUR-31 flights only. Incorporating flights to and from the Middle East, North Africa, the Balkan and Eastern European countries, will result in a somewhat different distribution.

[8] See chapter 3.

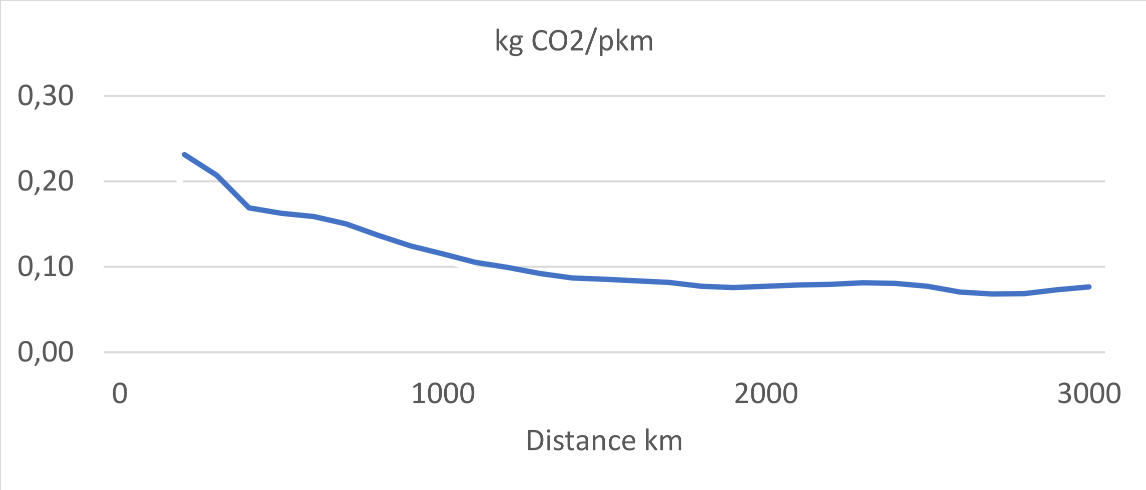

Figure 4: Specific CO_2 emission per passenger-kilometre (moving average of three 100 km distance classes calculated from database Annex A).

Trains can be an alternative for flying at distances below 1000 km.[9] The CO_2 emissions from intra-European flights shorter than 1000 km are calculated at 28 Mt. The number of passengers on these flights was 359 million in 2017[10], connecting 1539 city pairs[11] and covering 208 billion passenger-kilometres. More than 1,000 city pairs have a volume of air travel below 200,000 passengers a year (figure 5). The 18 city pairs with more than 2 million air passengers, account only for 14% of CO_2 from intra-EUR-31 aviation below 1000 km. These data show that aviation has a dense geographical network, in which very many city pairs are relevant for a modal shift to rail. The air passenger volumes are comparable to train passenger volumes. Four million passengers travel on the busiest train service in Europe while the tenth busiest carries 1 million passengers a year (Annex B).

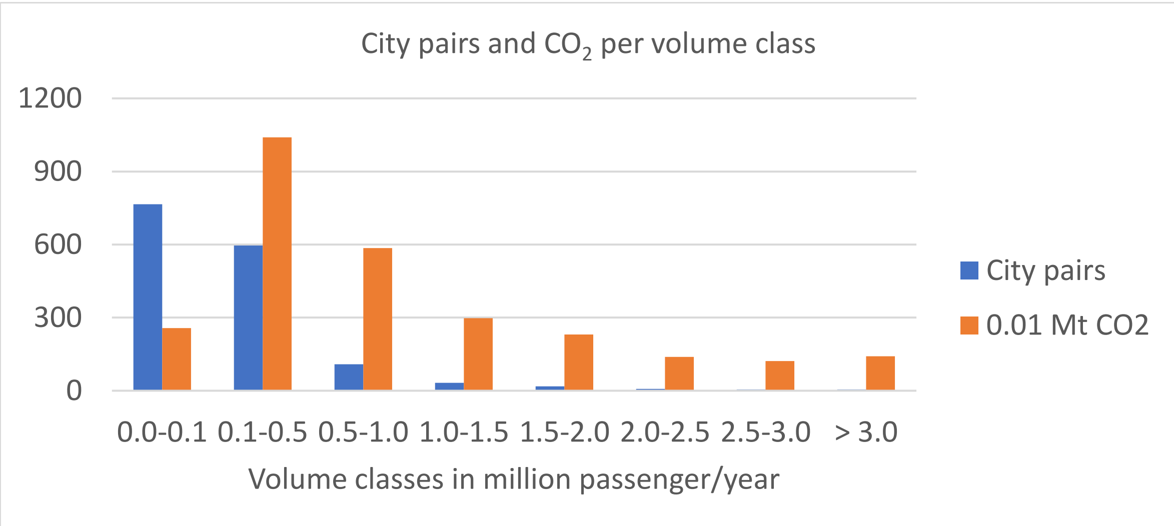

Figure 5: Number of city pairs and CO_2 emissions per passenger volume class for intra-EUR-31 flights below 1000 km (calculated from database Annex A).

[9] This will be underpinned in Chapter 5. Night trains can be attractive on larger distances, up to 1200 km. The potential for night trains will be discussed in Chapter 7.
[10] Passenger volumes, passenger kilometres and CO_2 emissions per city pair, are the combination of both directions in the present study.
[11] The actual number of routes is larger, because flights from smaller airports and with few passengers are not included in Eurostat (2019). See Annex A.

For travel to and from islands[12], it is hard for railways to offer a competitive service to aviation – both in travel time and costs. Ireland is, of course, best accessible by air and many islands are popular holiday destinations. Table 4 shows the top-10 aviation routes to an island. Total aviation CO_2 on the 24 island routes with more than 600,000 passengers a year, is 2.0 Mt. Several routes below 600,000 passengers also serve islands.

City pair	**Distance km**	**Million pax**	**Billion pkm**	**Mt CO_2**
Dublin-London	466	5.0	2.3	0.39
Belfast-London	530	2.5	1.3	0.20
Catania-Rome	539	2.0	1.1	0.15
Barcelona-Palma de Mallorca	202	1.9	0.4	0.06
Madrid-Palma de Mallorca	547	1.8	1.0	0.12
Palermo-Rome	409	1.6	0.6	0.10
Milano-Palermo	883	1.2	1.0	0.10
Cagliari-Milan	700	1.2	0.8	0.10
Amsterdam-Dublin	750	1.1	0.8	0.10
Cagliari-Rome	394	1.1	0.4	0.07
Total island routes with more than 600,000 passengers/year		31.2	15.0	1.99

Table 4: Intra-European aviation routes to islands (from database Annex A).

Building a bridge or tunnel for trains, could be considered to improve the rail connection to islands. However, the distances to cross are generally too large to make this feasible. An exception might be a crossing of the strait of Messina, between Sicily and mainland Italy. Shifting to electric aircraft might be a better option to decarbonize air travel to and from islands.

Subtracting the emissions from flights longer than 1000 km, as well as island connections, brings the focus of this study down to a target 26 Mt CO_2. This corresponds with 42% of the emissions from all intra-EUR-31 flights and 14% of total CO_2 from European aviation. The following chapters will estimate which share of this 26 Mt can be avoided by a modal shift from air to rail.

[12] Travel by ferry is required for both rail and road transport.

5. Travel time and distance

What makes people prefer a trip by train over an airplane? Or the other way around? The short answer is travel time. Of course, costs, reliability and comfort are also relevant to some extent. Traveling by train is generally more comfortable than by plane. The ticket price mostly favours a choice for aviation. But the strongest determinant for the market share of rail in the air/rail market, certainly is travel time (e.g. Steer Davies Gleave 2006; Dobruszkes et al 2014; Nordenholz et al 2017; Savelberg and de Lange 2018). This holds at least under current prices and levels of comfort.

The dominant influence of travel time corresponds with the historic long-term trends in mobility. Increased speed has been the main driving force in the succession of transport modes: from horse carriage, via train and car to aviation (Bleijenberg 2017b). And because the average travel time budget per person is in the long run constant, higher speed translates into longer travel distances and thus mobility growth (e.g. Grübler 1990; Schafer and Victor 2000; Bleijenberg 2017a).

Travel times by rail and aviation are collected for 58 European city pairs (Annex B). Figure 6 presents the comparison, including the required time at airports and railway stations. Only seven routes out of 58, have a shorter travel time by rail than by air. These are all connected by HSR. The travel time advantage of aviation increases with the trip distance.

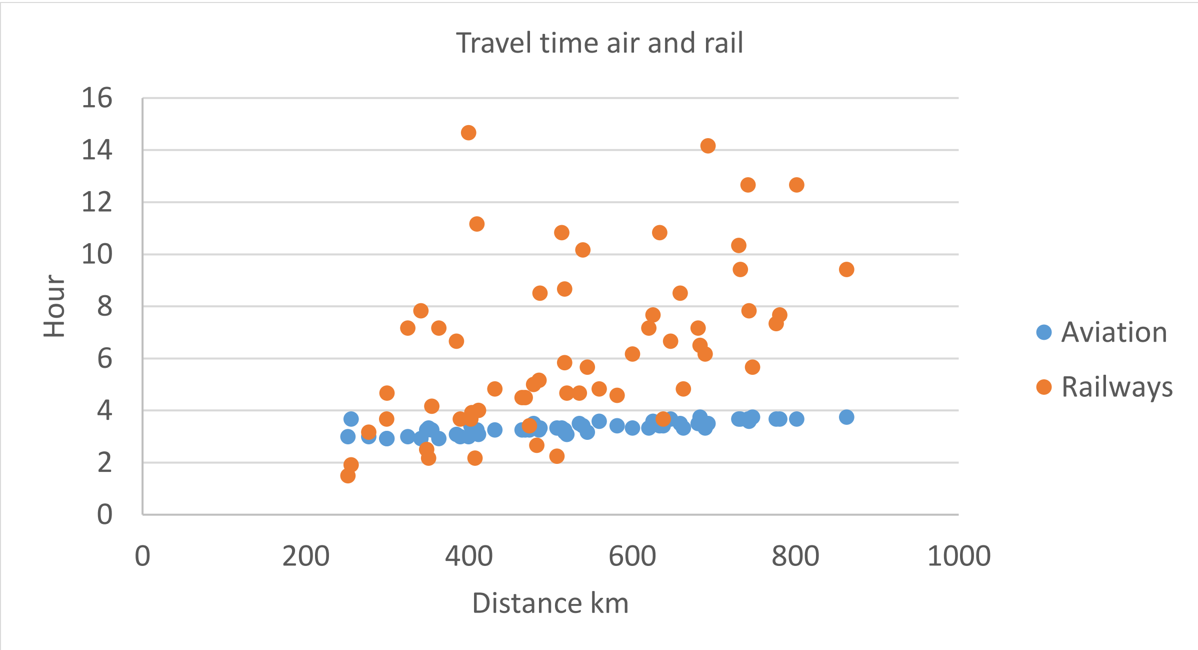

Figure 6: Travel time between airports and railway stations of 58 city pairs (from annex B).

When we compare travel times between city centres for the same city pairs, the competitive position of the train is better. Figure 7 gives this overview. Up to a distance of 700 km, the train can offer an equal travel time between city centres as aviation. It is not surprising that trips between the centres of large cities have a favourable travel time by train, because traveling to and from the airports is time consuming in large metropolitan areas. However, only part of the passenger's travels between city centres. Table 5 gives an overview of the 11 city pairs with a shorter travel time by rail than by air. All connections are between the centres of two large cities.

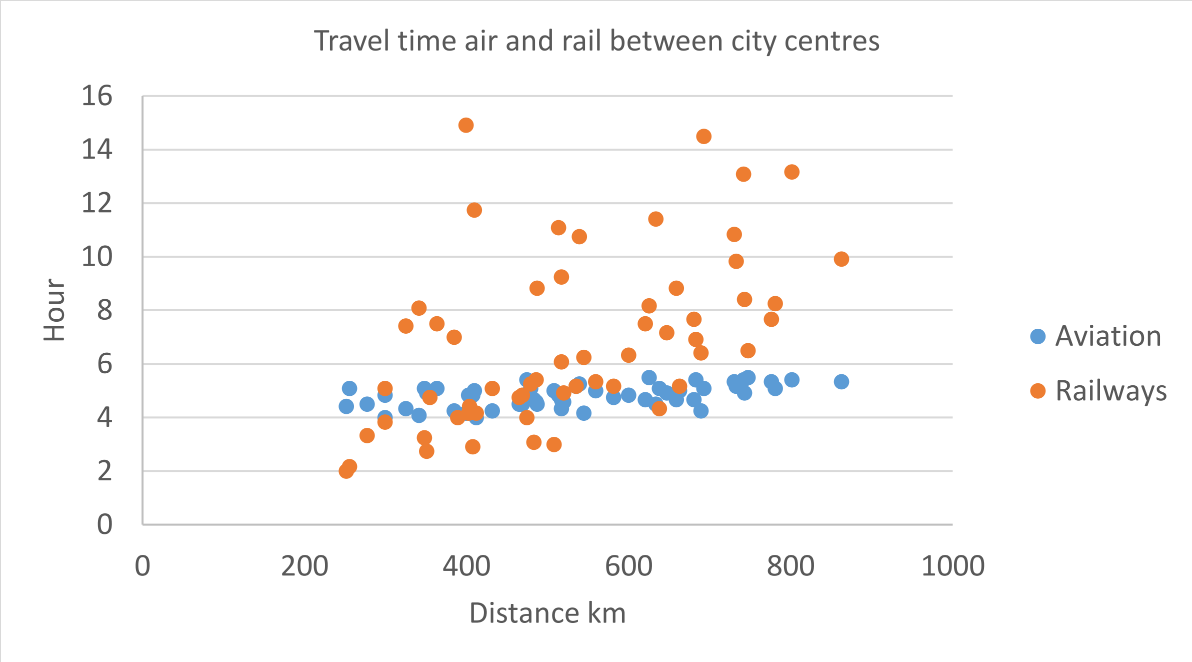

Figure 7: Travel time between 58 European city centres for aviation and railways (from annex B).

City pair	Distance	Time rail	Time air	Rail Mpax	Air Mpax	Share rail
Milano - Rome	474 km	4:00	5:25	4.0	1.3	75%
Barcelona - Madrid	483 km	3:05	4:40	3.9	2.3	62%
Lyon - Paris	407 km	2:55	4:50	3.4	0.7	83%
London - Paris	348 km	3:15	5:05	2.4	2.4	50%
Amsterdam - Paris	402 km	4:10	4:50	2.0	1.4	58%
Brussels - Paris	251 km	2:00	4:25	1.5	0.2	89%
Marseille - Paris	638 km	4:20	5:05	1.3	1.6	56%
Brussels - London	350 km	2:45	4:55	0.8	0.7	55%
Bordeaux - Paris	508 km	3:00	5:00		1.5	
Lisbon - Porto	277 km	3:20	4:30		1.1	
Berlin - Hamburg	255 km	2:10	5:05	1.1		

Table 5: Travel time between city centres at least 10 minutes shorter by railway than aviation (Annex B).

Because it is impractical to collect travel times, for both air and rail, on all European city pairs, the present study uses geographic distance as a proxy for travel time and as a main determinant for the modal split air/rail. Travel time by air is a well correlated function of distance and in the range considered here, only slightly increases with distance. This follows from the overview presented in figure 8, of travel times between 130 city pairs within Europe (Dobruszkes et al 2014). Therefore, there is no need to collect these data for each city pair.

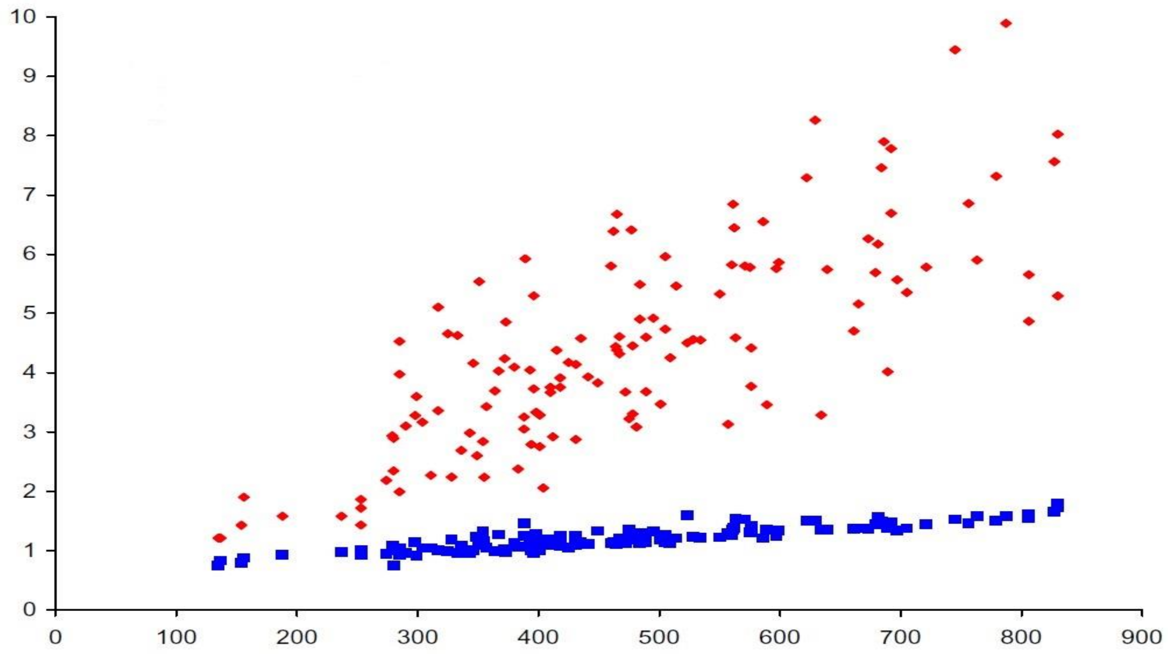

Figure 8: Travel time in hours by high-speed rail (red) and aviation (blue) between 130 city pairs in Europe connected by both HSR and aviation (Dobruszkes et al 2014).

The travel time by HSR also increases with distance, but it has a much greater variance, as figure 8 shows. This reflects the differences in net-speed of the 130 connections by HSR. Dobruszkes et al (2014) consider rail connections between city pairs as high-speed when part of the journey is travelled at a speed higher than 250 km/h. The net-speed is lower, because of the use of conventional track on part of the trip, detours from the geographical distance and intermediate stops. The net-speed between the investigated city pairs lies approximately between 100 and 200 km/h, which reflects an important variation in quality of the rail service.

As a next step, empirical data are presented on the modal split in the air/rail market, dependent on distance. Figure 9 gives a recent overview of 17 global HSR connections (Savelberg and de Lange 2018). A similar analysis is made for 34 European city pairs as shown in figure 10. Both sets of empirical data show a similar pattern. The best rail connections, have a mode share of 100% below 250 km and hardly any share above 1000 km. The line between these two points reflects the best rail services. However, many connections don’t perform as well as the best.

The presented empirical data on the modal split in the air/rail market, will be used to assess the impact of better rail services in chapter 7. As the resulting mode shares relate to the entire air/rail market, an estimate of the size of this combined market is made first, in chapter 6.

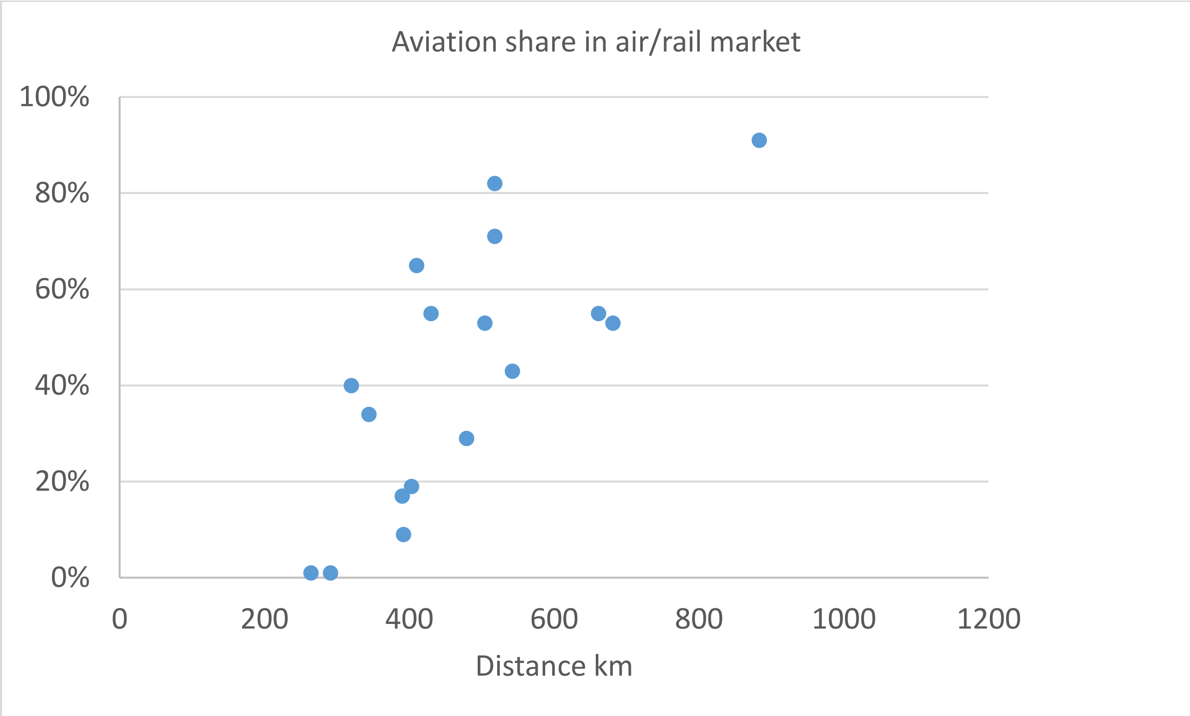

Figure 9: Share of aviation in the air/rail market for 17 worldwide HRS connections related to distance (data from Savelberg and de Lange 2018, based on Cheng 2010 and Nash 2013).

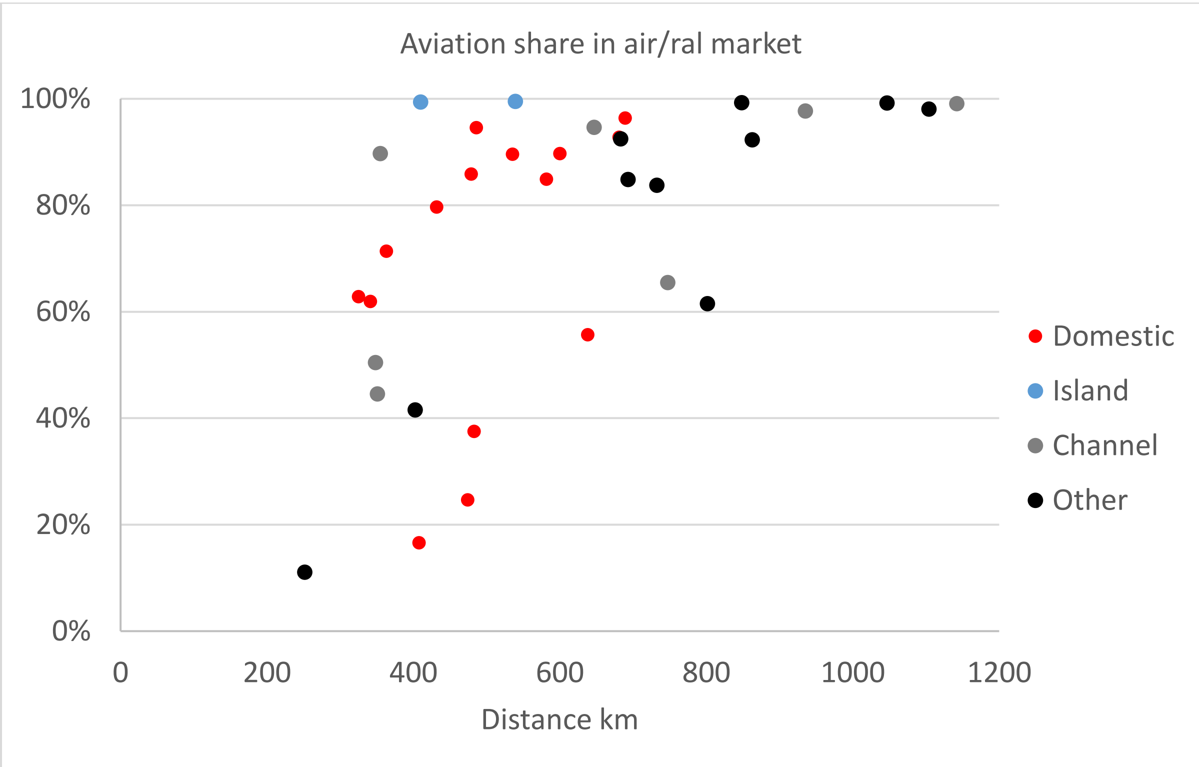

Figure 10: Share of aviation in air/rail market for 34 city pairs related to distance (data from annex B).

6. Estimate of the intra-European air/rail market

Data on the intra-EUR-31 aviation market are part of T&E's 'European Aviation CO_2 database' (Annex A). The number of passengers, passenger-kilometres and Mt CO_2 are available for city pairs, distant classes and volume classes. Unfortunately, similar data on the rail market are not available. To get an estimate of the entire intra-European air/rail market, a proxy has been made of passenger volumes by rail at distances between 200 and 1000 km.

The starting point is the 2017 figure of 470 billion passenger-kilometres by rail in the EU-28 of which 127 billion by HSR (EC 2019). Figure 11 shows the growth in rail and air volumes since 1995. Because three more countries are considered in the present study, 2.7% is added, corresponding with their population size.
A large share of travel by rail is within metropolitan areas and on short distances. This share isn't part of the air/rail market. Data from the ITF intercity passenger model are used to estimate the share of rail travel relevant for competition with aviation (ITF 2020). Following these model calculations, 79% of rail travel is on distances shorter than 200 km. The 21% passenger-kilometres on longer distances is considered relevant for the air/rail market. This results in an estimated rail volume of 200 billion passenger-kilometre in the intra-European air/rail market. This is divided over distance classes by linear diminution between 200 and 1000 km.

The figures 12, 13, 14 and 15 present overviews of the estimated air/rail market between 200 and 1000 km distance.

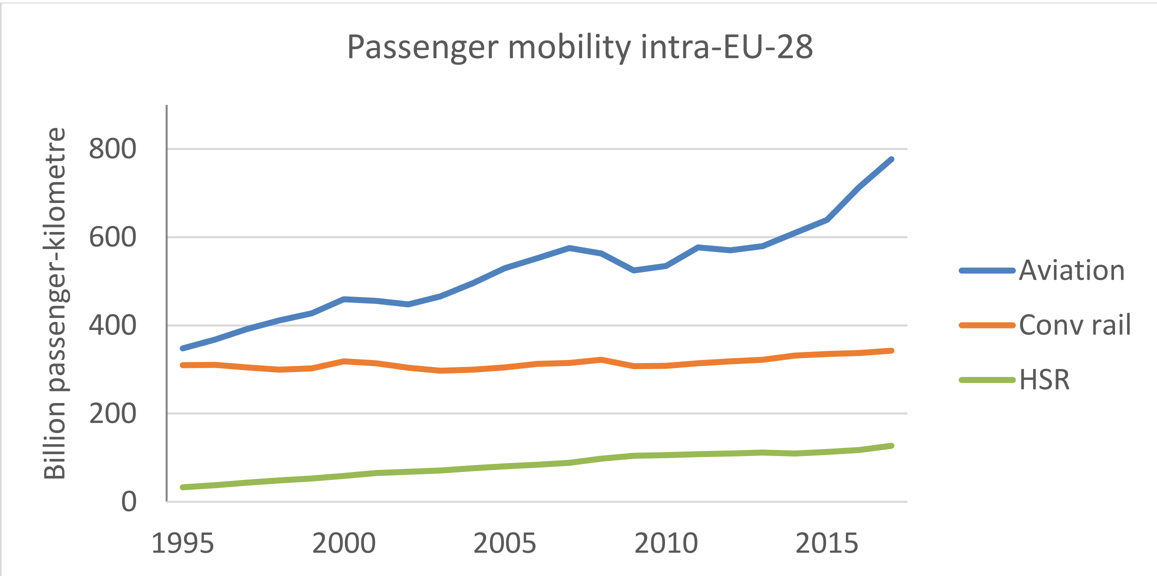

Figure 11: Passenger mobility 1995-2017 by conventional rail, high-speed rail and air intra-EU-28 (EU 2019).

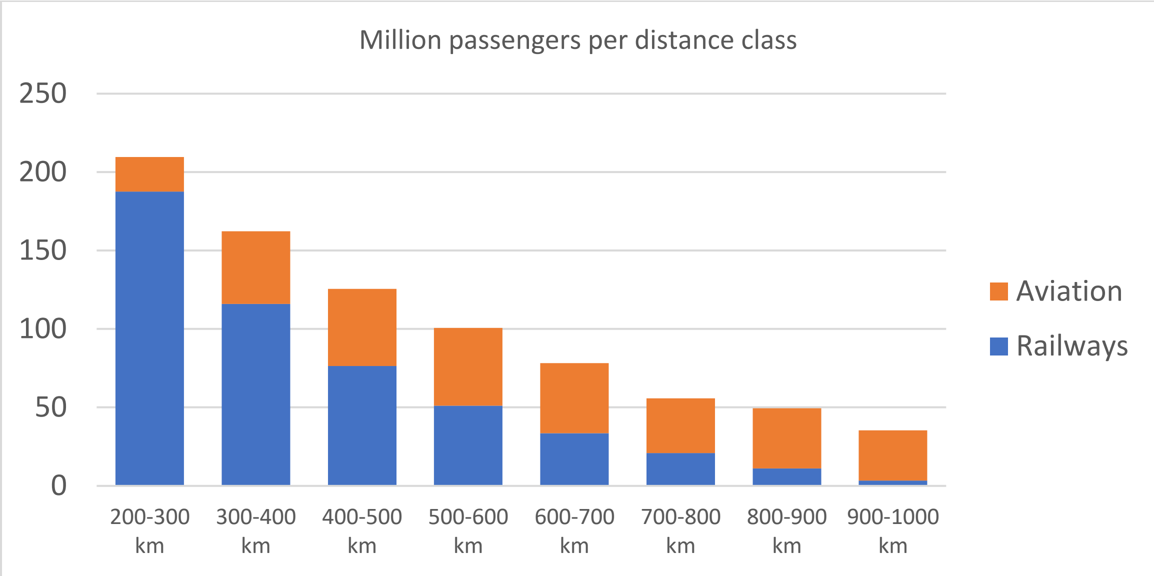

Figure 12: Passenger volume in the estimated air/rail market (own calculations).

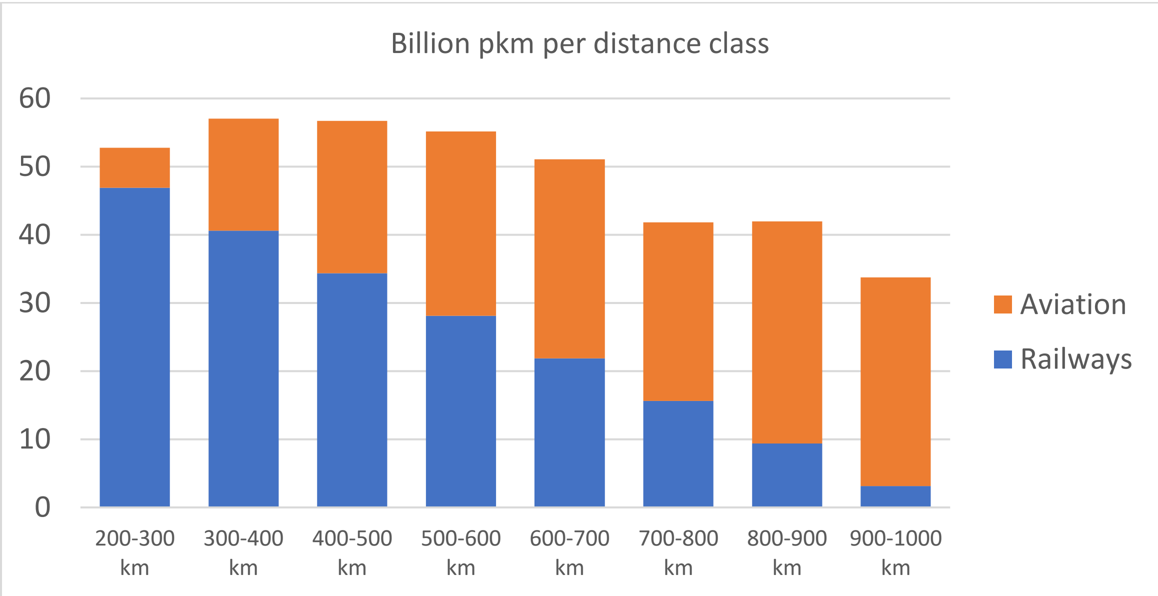

Figure 13: Passenger-kilometres in the estimated air/rail market (own calculations).

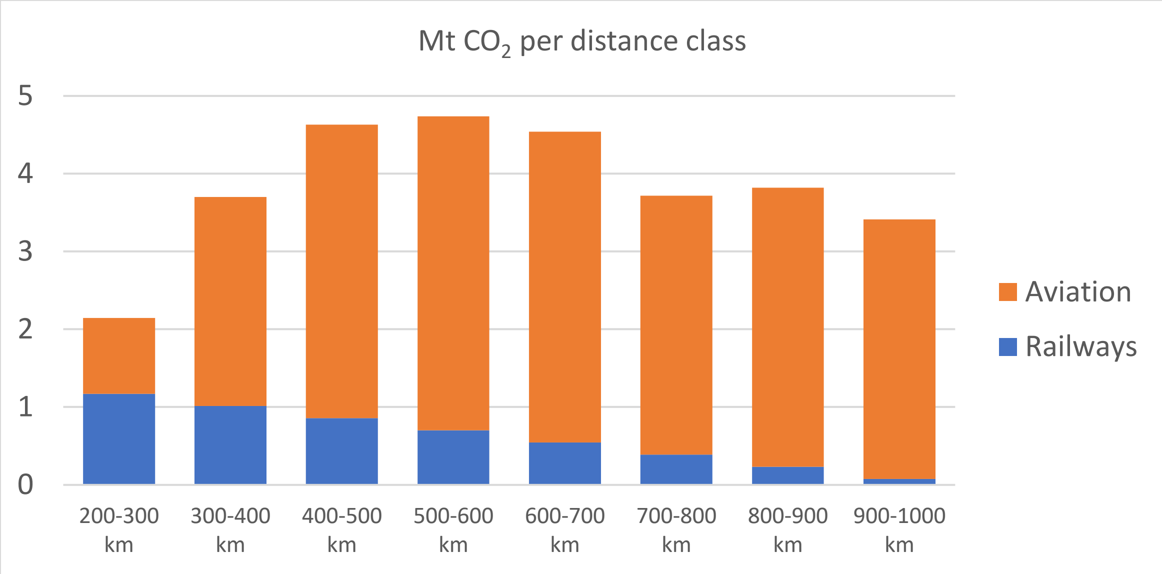

Figure 14: Mt CO_2 from the estimated air/rail market (own calculations).

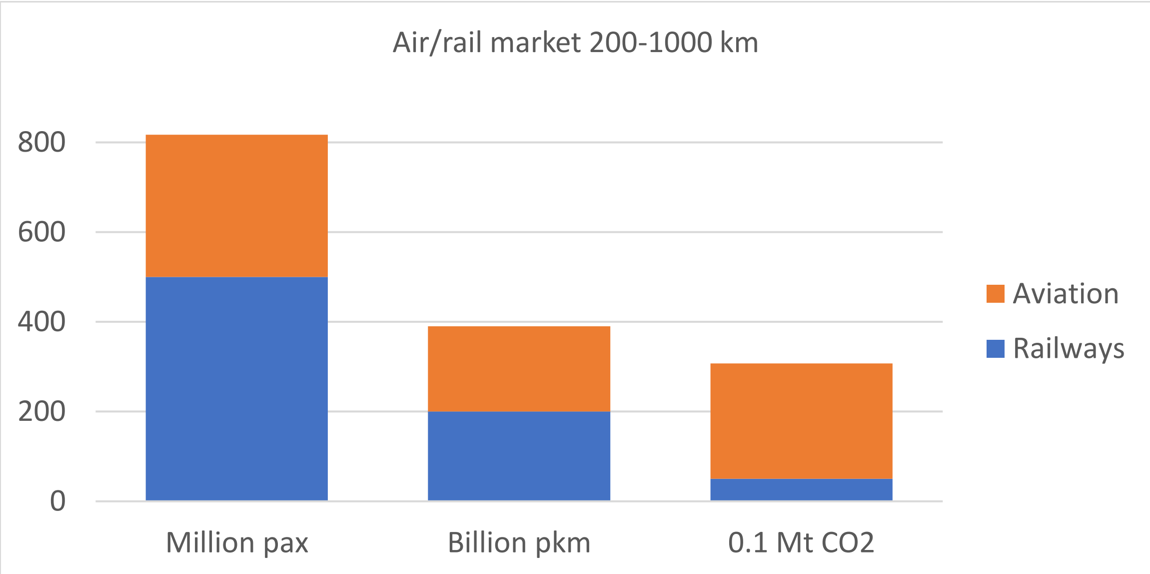

Figure 15: Passengers, passenger-kilometres and Mt CO_2 in the estimated air/rail market (own calculations).

A recent paper by Rebel (2019) made an estimate of the potential CO_2 reduction from intra-EU aviation by modal shift from air to rail, without making an estimate of the air/rail market. They apply a substitution factor on the aviation market, without taking account of the current share of rail travel. This leads to an overestimation of the additional potential for modal shift for city pairs which a contemporary favourable share of rail. This is illustrated with travel data between Milano and Rome (table 5). The current air share is 25% and according to the Rebel paper, this could go further down to 8% in their medium variant. This seems optimistic, because the best high-speed rail practise on this distance indicates an attainable air share of only 23% (figure 16 in next chapter).

7. CO_2 reduction by a modal shift from air to rail

There exists no European plan to improve the speed and quality of international rail services on distances between 200 and 1000 km. Proposed improvements of railway services mainly focus at national level, with some exceptions for cross border connections. This reflects the organization of the railway sector in national companies, with strong involvement of national governments. The European Court of Auditors (2018) summarizes the current situation in the title of one of their reports as “A European high-speed rail network: not a reality but an ineffective patchwork.”

To overcome this lack of a comprehensive plan, three general variants for improved railway services are assessed:
- Best practice. It is assumed that the modal split of the best performing rail links, apply to all connections competing with aviation. In practice this implies having high-speed rail between most large European cities.
- Trains 10% faster. This approach assumes that the net-speed between city pairs increases by 10% on all connections competing with aviation.
- 50% more night trains.

The reduction in CO_2 from aviation by these improvements is estimated, using the building blocks developed in the former chapters. No assessment is made of associated measures, costs and required time to realize these improvements.

Best practice
A first approach is to estimate the reduction in air travel when all rail services competing with air routes would have the same quality as the current best. The best practices in rail share can be derived from figures 9 and 10, corresponding with the line from ‘300 km/0% aviation’ to ‘1050 km/100% aviation’, as indicated in figure 16. Table 6 gives an overview of these ‘best’ rail links from figure 16. ‘Best’ means the highest rail share related to distance or in other words, close to the orange line in figure 16. All best connections are between large cities, benefitting from the fast access from HSR to the city centres. This implies that under the ‘best practice’ assumption, all major cities in Europe need to be connected by HSR. Additionally, it is assumed that all flights shorter than 300 km will shift to rail (except to and from islands).

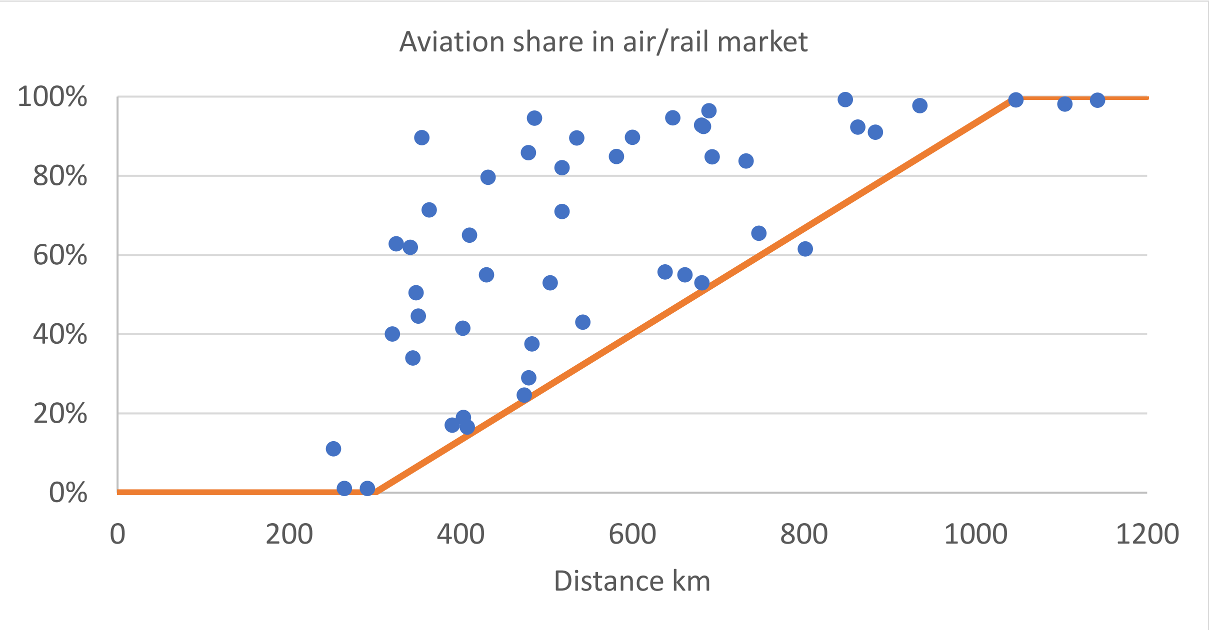

Figure 16: Best practice high-speed rail, dependent on distance.

City pair	Distance	Rail Mpax	Air Mpax	Share air
Tapeh - Koahsiung	291 km			1 %
Madrid - Sevilla	390 km	1.8	0.3	17%
Lyon - Paris	407 km	3.4	0.7	17%
Milan - Rome	474 km	4.0	1.4	25%
Marseille - Paris	638 km	1.3	1.6	56%
Tokyo - Heroshima	681 km			53%
London - Lyon	747 km	0.6	0.3	65%
Rome - Stuttgart	801 km	0.1	0.1	62%

Table 6: Best practice city pairs, dependent on distance (Savelberg 2019 and Annex B).

Using the data from the estimated air/rail market, it is calculated that 110 million passengers will shift under this assumption from air to rail, thus reducing the CO_2 emissions from aviation by 7.4 Mt. The shifted passenger kilometres add up to almost 50 billion. This is a 25% increase in rail travel on distances between 200 and 1000 km. This estimate must be regarded as a maximum, because not all air routes can be linked by HRS against reasonable costs. This estimate implies, the other way around, that an additional 19 Mt CO_2 from intra-European aviation can't be avoided by a shift to rail, unless a breakthrough in rail technology is realized.

Almost 9,000 km of high-speed rail track was operational in 2018, of which 8,000 in the four countries with their own, mainly domestic, high-speed services: France, Spain, Germany and Italy (EC 2019). Since 2010 2,600 km were added. The last opened line was between Copenhagen and Ringsted in Denmark. The transport volume on EU-28 HSR was 127 billion passenger kilometre in 2017 (EC 2019). The only border crossings by high-speed rail are Paris-London-Brussels-Amsterdam and Barcelona-Perpignan, although the latter doesn't (yet) offer a fast connection to the French high-speed network. The high-speed rail network is only one tenth of the network of intra-European air services, which can be estimated at 100,000 km between 170 city pairs.[13] The number of direct connections by air between European destinations, has grown by more than 6% per year, over the last two decades (Airbus 2019).

Several new high-speed tracks have been proposed in Europe (UIC 2018). Some of these, however, have been shelved. An assessment of the European modal shift policy concludes that the goal of tripling the length of HRS-lines in 2030, as stated in the 2011 White paper, seems unlikely to be achieved. Between 2011 and 2018 the network is enlarged by only 34% (TRT and TEPR 2019). High investment costs and uncertainty about the revenues generate doubts. To make a reasonable business case for new high-speed rail track, several million passengers are needed (Nash 2013).[14] This can be achieved by connecting two large cities, such as London and Paris, or by connecting several cities along the new track ('string of pearls'). Specific feasibility studies are required to assess which new high-speed links are viable.

Donners (2016) designed an enlarged high-speed rail network for Europe. Calculations with the RHDHV European passenger model, indicate that this will reduce aviation on distances between 200 and 1000 km by 18 billion pkm (RHDHV 2020). This reduction in air travel is calculated with as reference a modelled 'optimized' existing rail network.[15] Shifting 18 billion passenger-kilometres from aviation, reduces CO_2 by 2.5 Mt.[16]

[13] Estimated with the model for city pairs between 250 and 1000 km, with at least 500,000 passenger a year.
[14] The break-even point depends on several factors, of which the construction cost is the most important.
[15] See Donners (2016) for description of the model and the two rail scenarios.
[16] Average of 0.14 kg CO_2/pkm on distances between 200 and 1000 km.

In assessing the environmental benefits of new HSR-links, the gains in modal shift from air and road, will be partly offset by a shift from conventional rail and by generating extra mobility. Reducing rail travel time from 4 to 2 hours, will typically attract travellers of which 50% are new, 40% come from aviation and 10% from the car (UIC 2018).
Next, constructing a new track also causes emissions of CO_2. These may add up to 1.5 Mt for building a 300 km line. The carbon break-even point is estimated to be around 12 years after commissioning of the project (UIC 2018).

Trains 10% faster
A second approach to assess the modal shift from air to rail, is to estimate the impact of faster train connections on all links competing with aviation. Faster train services between city pairs can be achieved by higher cruising speed, less or shorter stops, faster border crossings and better train paths. To illustrate the impact of such improvements, it is assumed that all train services reduce their travel time by 10%. Using the data from the estimated air/rail market, it is calculated that this can make roughly 50 million passengers shift from air to rail.[17] This corresponds with 27 billion passenger-kilometre and a reduction in CO_2 by 3.7 Mt. This equals 14% of the 26 Mt CO_2 caused by intra-EU city aviation, below 1000 km and excluding island connections. Intra-European rail travel will increase by 13% on distances between 200 and 1000 km.

This calculated 14% reduction in CO_2 from aviation, is higher than the 7% estimated for rail travel time reductions in the German long-distance travel market (Nordenholz et al 2017). However, this publication doesn't state by how much the rail travel times were assumed to go down. Rail travel is projected to increase 16% in this scenario, air travel declines by 6% and car driving by 2%. Mobility of all modes combined, increases slightly, by 0.3%.
Another study assessed the impact of travel time reductions by on average 30% on 8 existing HSR-lines (Steer Davies Gleave 2006). This is estimated to increase the market share of rail by on average 8%. If this would apply for the entire intra-European air/rail market, roughly 4.3 Mt CO_2 will be avoided.

It is not possible to indicate the required costs and measures, to achieve the assumed 10% reduction in travel time on a large part of the European rail network. Despite this lack of information, the estimated 3.7 Mt reduction in CO_2, can serve as an indication of the impact from improved rail services. Of course, larger increases in train speeds, will result in a stronger reduction in air travel. Priorities in rail improvements can be made by analysing their impact on CO_2 from aviation.

Night trains
Night trains can offer an alternative for daytime aviation trips. Most attractive are train departure times between 19:00 and 23:00, which is in many cases later than the last departing flights. Arrival times between 7:00 and 9:00 the next day are attractive, because this is earlier than many flights. Within these timeframes, traveling by night train has less time loss than aviation. With an average speed of around 80 km/h, this results in a potential market for night trains at distances between 800 to 1200 km (DB 2013; Savelberg 2019). The connected urban areas need to have at least one million inhabitants to make a night train connection viable.

Currently, the Austrian railway company ÖBB offers most international night trains in Europe. 19 cities are connected through 7 main Nightjet services. The cities include Wien, München, Hamburg, Berlin, Düsseldorf, Brussels, Venice, Milan and Rome. In 2018 1.4 million passengers travelled by Nightjet. Domestic night trains are run in e.g. Italy, Romania, Poland, France, the UK and Sweden. The

[17] The average current performance of rail services is estimated to correspond with the line between '200 km/100% rail' to '950 km/0% rail' in figure 16.

total passenger volume of night trains in Europe is estimated at 6 million a year, as far as data were obtainable (Steer Davies Gleave and Politecnico di Milano 2017). This reduces CO_2 from aviation by around 0.6 Mt.[18]

ÖBB expanded its night services during the last years and intends further enlargements. On the other hand, Deutsche Bahn ended its night trains in 2016 and SNCF limited its night services to two routes, from Paris to Toulouse and Briançon. The market for rail travel during nights is slowly declining. Main factors are the growth in daytime high-speed rail services and the rise of low-cost carriers. HSR and night trains compete partly for the same passengers, which explains that Austria – without HSR – increases its night services, while Germany and France reduce theirs. Other obstacles for the operation of night trains are lack of track capacity during the night, due to maintenance works and slow freight trains, and lack of capacity at main stations during the morning peak. National differences in gauge width and power voltage also need to be overcome at many international connections (Steer Davies Gleave and Politecnico di Milano 2017).

A night train network has been designed, connecting Germany with other European countries (Walther et al 2017). Seven routes are proposed, e.g. from Hamburg to Milan, from Berlin to Paris and from Amsterdam to Budapest. Next, the impact of these night services on the passenger volumes for aviation, coach and car were assessed. The changes in travel volumes per mode are translated in CO_2 emissions. The reduction is calculated at 0.05 Mt CO_2, with a maximum scenario of 0.10 Mt. These estimates include the diminished travel by car, bus and plane, as well as the extra CO_2 caused by the growth in rail traffic.

Another way to gain insight into the potential reduction of aviation CO_2, is to assess the impact of one extra night service. A night train typically boards 80,000 travellers a year (Savelberg 2019). Assuming an average 1000 km trip per passenger, this corresponds with 80 million pkm per year. With an average CO_2 emission from aviation at these distances of 0.10 kg per passenger-kilometre, this results in 0.008 Mt per extra night service. If 30 services are added between the larger cities in Europe on the relevant distances, this would attract 2.4 million rail travellers from the air and roughly reduce CO_2 from aviation by 0.24 Mt. This is a small share of the current aviation market between 800 and 1200 km, which covers 130 million passengers with 13 Mt CO_2 emitted.

Capacity of the rail network

It is not possible in the present study to assess whether existing rail capacity is sufficient for the trend-wise annual growth of around 1.5%, plus the desired modal shift from air and car. In this section it is assumed that 40 billion rail passenger-kilometres come over from aviation. Both factors combined result in a growth of rail pkm from 483 in 2017 to 720 billion in 2040. This is a growth of 50% in 23 years. Considering only distances between 200 and 1000 km, relevant for the rail/air competition, the rail market increases from 200 to 290 billion pkm.[19] The impact of the trend-wise annual growth is larger than that of the modal shift from air to rail.

Information about track utilization – train-kilometres per track-kilometre – indicate that most countries have enough opportunities for growth on existing rail track (Steer Davies Gleave 2015). The Netherlands has the highest track utilization in the EU-28 with almost 50,000 train-kilometres per track-kilometre (data 2012). Most countries run less than half this number on their network and can probably accommodate substantial growth. In 2012 seven countries had a utilization of more than 25,000 train-kilometres per track-kilometre and might run into capacity constraints with the indicated growth in train travel. These countries are Belgium, Denmark, Germany, Luxembourg, Netherlands, Austria and the United Kingdom. This approach, using national averages for track

[18] Average of 0.10 kg CO_2/pkm on distances between 800 and 1200 km.
[19] Assuming a trend-wise growth by 1% a year on long-distance rail travel.

utilization, is of limited value, because specific tracks might face capacity constraints, while other tracks are heavily underutilized. This can only be investigated in capacity studies for specific routes and networks.

Existing HSR-links will generally not experience capacity constraints. The busiest high-speed section in Europe is between Paris Gare de Lyon and the split Lyon/Dijon. 240 trains use this track each day (2017), carrying 44 million passengers during the year (SNCF 2019). This corresponds with 400 flights per day (300 seats per aircraft). SNCF indicates that the current maximum capacity on the section Paris–junction Lyon/Dijon is approached, and therefore plans to expand the train capacity from 13 trains per hour in each direction, to 16 trains in 2030. This is achieved by implementing the advanced European safety system (ERTMS, European Rail Traffic Management System). The capacity will then be increased to about 54 million passengers a year. So, the capacity of high-speed rail track is large compared to the number of passengers flying between the busiest city pair: almost 5 million between Dublin and London. However, capacity bottlenecks may occur when rail travel between several city pairs use the same track section. Such as the section between Paris and the Lyon/Dijon split of the French high-speed rail network.

The Channel Tunnel might in the future limit the growth of rail traffic between England and mainland Europe. In 2018 almost 11 million passengers crossed the Channel with Eurostar. In addition, the tunnel is used by freight trains, as well as shuttles for cars, coaches and trucks. Another 11 million passengers cross the channel by shuttle. It is hard to get information about the capacity of the tunnel and to what extend this is currently used.[20] A document from the European Commission (EC 2013) states that 43% of the capacity of the Eurotunnel was unused at that time. With some growth since 2013 it is estimated that currently 12 out of the 20 available standard train paths are used. The capacity can ultimately be increased to 30 paths per hour and per direction (Noultan 2001). This requires deployment of moving block signalling. Further assuming that the split between shuttles, freight trains and passenger trains, will not change, the maximum amount of train passengers is estimated at 27 million a year. This results in a spare capacity of 16 million train travellers per year. This is smaller than the number of passengers currently flying across the Channel (or North Sea) at distances below 1000 km: 30 million a year.[21] So, the capacity of the Channel Tunnel might become a bottleneck when pursuing a substantial modal shift from air to rail. However, several solutions can be considered:

- Expanding the capacity from 20 to 30 standard train paths should be realized in due time.
- Increasing the share of passenger trains, while reducing the share of shuttles. This might require new arrangements between France, UK and the Eurotunnel company.
- Making short distance flights by zero-CO_2 electric aircraft, so freeing up capacity in the tunnel for modal shift for other city pairs. This is especially attractive for travel between cities where the train makes a detour, such as Amsterdam-London (4.7 million passengers a year) and Amsterdam-Manchester (1.0 million passengers a year).

Conclusion

Table 7 summarizes the results of the three developed approaches to estimate the CO_2 reduction in the air/rail market. Main conclusion is that around 4 to 7 Mt CO_2 from intra-European aviation, may be avoided by a modal shift from air to rail. This corresponds with 6% to 11% of the CO_2 emissions from intra-EUR-31 aviation and with 2% to 4% of CO_2 from all aviation fuel bunkers in EUR-31. To achieve this gain, faster intra-European rail services are required. In combination with the trend-wise growth, train travel on distances between 200 and 1000 km will have to increase by 40% to 50% in

[20] A request for this information in December 2019 at the Eurotunnel company – part of the Getlink Groupe – has not been answered.
[21] City pairs above 600,000 passengers per year and excluding islands. Therefore, excluding all air travel between Ireland and the continent.

2040. The present study did not investigate measures and costs, needed for the assessed improvements of rail services.

	Reference	Best practice		Trains 10% faster		Night train +50%
Air passengers	317 Mpax	207 Mpax	-35%	270 Mpax	-15%	-2.4 Mpax
Rail passenger	500 Mpax	613 Mpax	+23%	660 Mpax	+32%	+2.4 Mpax
Air pkm	190 Bpkm	142 Bpkm	- 25%	163 Bpkm	-14%	- 2.4 Bpkm
Rail pkm	200 Bpkm	248 Bpkm	+24%	227 Bpkm	+13%	+2.4 Bpkm
Air CO_2	25.7 Mt	18.3 Mt	-7.4 Mt	21.4 Mt	-4.3 Mt	-0.24 Mt
Rail CO_2	5.0 Mt	6.2 Mt	+1.2 Mt	5.7 Mt	+0.7 Mt	+0.06 Mt

Table 7: Overview of the estimated impact of three assumed railway improvements on the air/rail market between 200 and 1000 km.

8. Dynamics in the European travel market

The estimated potential CO_2 reduction in the previous chapter, is based on a static analysis for the year 2017. Before conclusions can be drawn, some important dynamics in the European travel market will be discussed. Expected changes in travel volumes and specific emissions, might influence the magnitude of environmental benefits from a modal shift from air to rail. When airport capacity is constrained, environmental gains from modal shift will be lower. And improved railway services will not only change the modal split but will – ceteris paribus – also induce new passenger travel.

Travel volumes and emissions
Intra-European aviation is expected to remain growing, while specific emissions per passenger-kilometre will decline. These opposite developments result in projected CO_2 from European aviation between -18% and +85% in 2040 (Figure 2; EU 2019). Growing aviation emissions will enlarge the positive impact from improved rail services. However, stronger policies to combat climate change, will likely not only lead to improved rail services, but also to reduced specific emissions from aviation. Therefore, it is not likely that anticipated developments in travel volumes and emissions, will have a large impact on the estimated reduction potential.

Specific emissions for rail travel are estimated at 0.025 kg CO_2/pkm (current EU average). This number is expected to drop towards zero, as a consequence of further decarbonization of the European power sector. The extra CO_2 from more rail passengers, were not included in the estimated 4 to 7 Mt reduction. So, these were already implicitly set at zero.

Average CO_2 emissions from aviation at distances between 200 and 1000 km are estimated at 0.140 kg CO_2/pkm.[22] Because the specific emissions from rail are much smaller than from aviation, travel by rail is preferred from an environmental viewpoint. This advantage will likely remain for at least several decades. On the long run and under fierce climate policies, specific aviation emissions might go down to the current level of rail, as shown in table 1 (ITF 2019).

Airport capacity and short flights
If aviation growth is constrained by airport capacity, shifting passengers from air to rail, will free up airport capacity for other flights. The expected environmental gain may partly, or even more than fully, disappear. Eurocontrol (2018) projects a shortage of 1.5 million flights in 2040, or 8% of unrestrained demand, in its most likely scenario. France, Germany, Netherlands and the United Kingdom are expected to have the largest shortages, more than 250,000 flights per year.

Shifting short flights to rail has several benefits. Airline costs per pkm are higher for short flights than for long-haul flights (Steer Davies Gleave 2006). The specific emissions from short flights are also higher: average 0.17 kg CO_2/pkm below 200 km, compared to 0.14 for flights between 200 and 1000 km. These advantages stimulate cooperation between airlines and railway companies, to offer customers one ticket for train travel to the airport hub and the connecting flight. Among others, Lufthansa and DB developed the Lufthansa Express Rail as Point-to-Point Feeder to Frankfurt airport (DB 2020).

In case of shortage of airport capacity, shifting a short flight or feeder to rail, can result in higher emissions. A 277-seater on a 1000 km trip, emits 8 times more CO_2 than the 140-seater on a 200 km trip, which was replaced by a train feeder. However, when the flight with the 277-seater, was formerly flown from a nearby airport without capacity shortage, the environmental gain is positive.

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[22] Average derived from T&E's 'European Aviation CO_2 Model' (Annex A). Specific flights can have a much larger or somewhat smaller emission factor. Non-CO2 emissions from aviation make its impact on climate change two to four times larger (chapter 3).

So, airport capacity and the changes in the wider aviation market, must be considered, when assessing the environmental impact of modal shift.

Intermodal travel market
The intermodal travel market is dynamic and flexible. Many people can easily change from one mode to another, when the one becomes better (faster) or the other worse (slower). The quality of travel also influences spatial behaviour of people and companies. The now classic example is the opening of the high-speed rail link between Paris and Lyon, which made commuting feasible between these two cities. In general, improving one mode – rail in the present study – will not only cause a shift from other modes – aviation and road –, but will also generate new mobility. Faster travel doesn't save time, but results in longer distances, thus growth in overall mobility (Bleijenberg 2017a and b). Shortening the travel time by rail from 4 to 3 hours, will attract new passengers of which 35% shift from aviation, 25% from the car and 40% is induced travel (UIC 2018). Induced travel needs to be incorporated in assessments of the environmental benefits of rail improvements.

Induced travel by faster trains can be counteracted by discouraging air travel. This contributes to the modal shift from air to rail and reduces total mobility growth somewhat. A combination of discouraging aviation and improving rail services is needed to realize the CO_2 reduction of 4 to 7 Mt, as estimated in chapter 7. Pricing aviation is an obvious way to reduce its attractiveness somewhat. Several countries have or consider implementing ticket and fuel taxes on aviation (CE Delft and SEO 2019). This is supported by economic and environmental arguments. International aviation is currently exempt from VAT and environmental costs are not included in the ticket price. Additional to national aviation taxes, a tax scheme for aviation at European level is both feasible and effective. Distortion of competition in the global aviation market can be avoided by a proper design of the aviation charge (Bleijenberg and Wit 1998). There are no legal obstacles either for implementing a European kerosene tax (Pache 2019).

Sustainable aviation
A modal shift from air to rail can only deliver a modest contribution in the pursuit of sustainable aviation. Improvements in energy efficiency of engines, aircraft and operations will continue. Zero-CO_2 electric aircraft might become an option at distances below 1000 km, especially suited for island routes, where rail is not an option. And synthetic kerosene from wind and solar power might become available to replace fossil fuels. Views on how global aviation can decarbonize are developed and presented by the International Transport Forum (ITF 2019) and the Energy Transitions Commission (ETC 2018). Although many developments towards zero-CO_2 aviation can't be foreseen now, it is important that the needed change is ignited now.

9. Conclusions and recommendations

This final chapter draws the overall conclusions and ends with recommendations for the railway and aviation industries, for national and international governments and for travellers.

Conclusions
The potential reduction in CO_2 from intra-European aviation, by a modal shift from air travel to railways, is estimated at 4 to 7 Mt. This corresponds with 6 to 11% of the CO_2 emissions from intra-EUR-31 aviation and with 2 to 4% of CO_2 from all aviation fuel bunkers in EUR-31 (figure 17). To achieve this reduction in CO_2, a combination of measures is required, both to improve speed and quality of international rail services and to discourage air travel. Train travel in Europe on distances between 200 and 1000 km needs to increase by around 50% in 2040. This includes the new passengers coming over from aviation plus the trend-wise growth of 1% per year. The present study did not investigate measures and costs, associated with the required reduction in travel times by rail. Further research needs to indicate which share of the estimated potential can be achieved against reasonable costs.

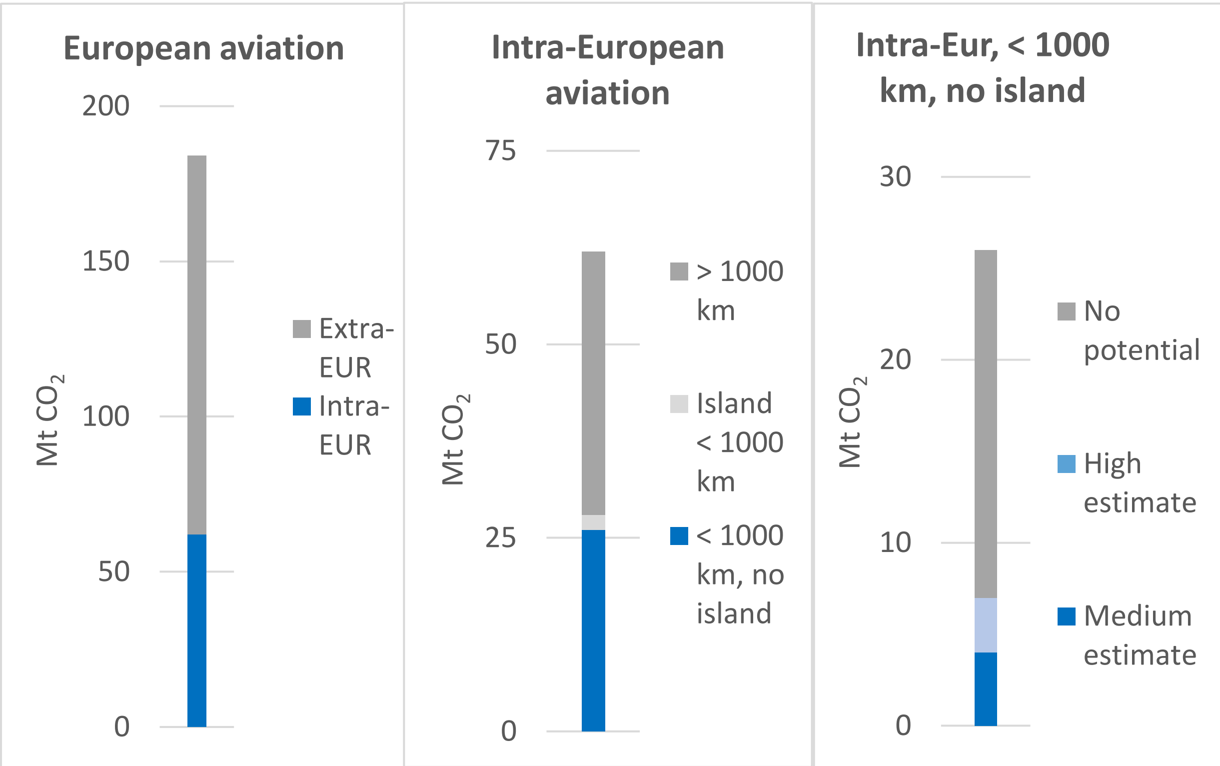

Figure 17: Potential CO_2 reduction by modal shift from air to rail, relative to emissions from European aviation and intra-European aviation (be aware of the different scales).

Shifting travellers from air to rail, not only reduces CO_2, but also the non-CO_2 impact from aviation on climate change (chapter 3). On intra-European flights, the non-CO_2 impact is roughly the same as the CO_2 impact (Scheelhaase 2019). Therefore, the reduced contribution from intra-EUR-31 aviation to climate change, is roughly double the estimated CO_2 reduction.

The lack of data on the intra-European rail market limits the accuracy of the estimated potential. Future studies may reduce this uncertainty. However, the order of magnitude of the outcome appears robust.

Next, it might be questioned whether the sensitivity of travel time for mode choice between air and rail, will change in the future. This is unlikely, because travel time has been the dominant determinant of mode choice, for the centuries since motorized travel took off (Grübler 1990; Schäfer and Victor 2000; Bleijenberg 2017a). And faster travel results on the long run almost inevitably in longer trip distances and thus mobility growth (Schäfer and Victor 2000; Bleijenberg 2017a and b). There are no convincing reasons to suppose that these driving forces behind mobility will become less strong than they have been in the past.

Recommendations to the railway industry

The main recommendation is to develop a truly European railway approach, to compete better with the intra-European aviation market. Specifically:

1. Develop a European plan and strategy to reduce travel times of international trains, by e.g. better timetables, train paths and higher priority, reduced time losses at border crossings, better interoperability, less stops at small intermediate towns, higher speeds of conventional trains and increased capacity through advanced train management (ERTMS).
2. Develop a European marketing approach. This includes easy search and purchase of international train tickets (as for aviation) and financial compensation for missed connections, also when caused by delays of another train company.
3. Assess the environmental impact of railway improvements on the entire long-distance travel market. This includes reduced CO_2 from air and road, as well as induced travel. Long-term investments need to be assessed with future specific emissions of all modes
4. Disclose information on the passenger volumes by train between city pairs (as is available for aviation).
5. Shift to 100% renewable energy. Intra-European rail emits currently around 12 Mt CO_2 per year.

Recommendations to the aviation industry

The main recommendation is to strongly reduce the environmental impact on the short, medium and long term. This includes:

1. End scheduled services for which rail offers a reasonable alternative.
2. Intensify the efforts to increase energy efficiency of engines, aircraft and operations.
3. Invest heavily in development of zero-CO_2 aviation, such as electric aircraft and synthetic fuels.
4. Offer customers the option to buy a (partly) green ticket, guaranteeing that for their energy consumption, zero-CO_2 fuel is used (partly). The additional costs are incorporated in the green ticket price.
5. End the current ineffective compensation schemes offered with tickets, which are not aimed at decarbonizing aviation.

Recommendations to governments

Th main recommendation for the EU and national governments, is to develop a tight and consistent climate policy for the intra-European travel market. This includes:

1. Request the European railway industry to develop a strategy, plans and marketing, to improve the competitive position of international trains. Request also that they disclose information on the travel volumes between cities.
2. Introduce taxes on aviation, to compensate for the lack of VAT on international aviation and to internalize the external costs from aviation.
3. Assess licenses for airport expansion with respect to their compatibility with the Paris Agreement. End all (implicit) subsidies and financial support to the aviation industry.
4. Develop a European policy to end the competition between countries to attract passengers to their domestic airports at the expense of others.
5. Assess the environmental impact of all policies – including funding for transport infrastructure – on the entire long-distance travel market.

6. Countries with a large amount of CO_2 from domestic aviation, need to develop national policies to reduce this. France, Spain, Italy, Germany, United Kingdom and Norway emit more than 1 Mt CO_2 (table 2).
7. Kick off the needed industrialization of the production of green synthetic kerosene as soon as possible. A blending obligation is an effective and efficient policy instrument to achieve this (E4tech et al 2019).

Recommendations to travellers

The main recommendation is to travel green and less.

1. Choose the train instead of the airplane. On distances between 100 and 500 km, the train emits only 15% of the CO_2 relative to the plane. This is an average, which can be very different for specific trips. The UIC EcoPassenger[23], or similar tools, can be used to assess the emissions of all different modes for specified trips.
2. If no suitable rail connection exists, consider changing the destination to one with a rail connection. This will stimulate better railway services and locating activities near railway stations.
3. Demand from the aviation industry, that they offer zero or low-CO_2 tickets for a higher price, which includes the additional costs to limit emissions. Do not use the ineffective compensation schemes, which are not helping to decarbonize aviation.
4. Demand from the railway industry improved speed and services for international train trips.
5. Support national and international policies to diminish CO_2 from long-distance travel.

[23] EcoPassenger.org

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Annex A - European Aviation CO_2 database

CO_2 emissions from European City Pairs

Authors : *Juliette Egal, Transport & Environment*
Thomas Earl, Transport & Environment

The European Aviation CO_2 database was developed by Transport & Environment in conjunction with the Air2Rail study - in order to calculate CO_2 emissions from aviation at city pair level - but aims at serving other applications in the future.

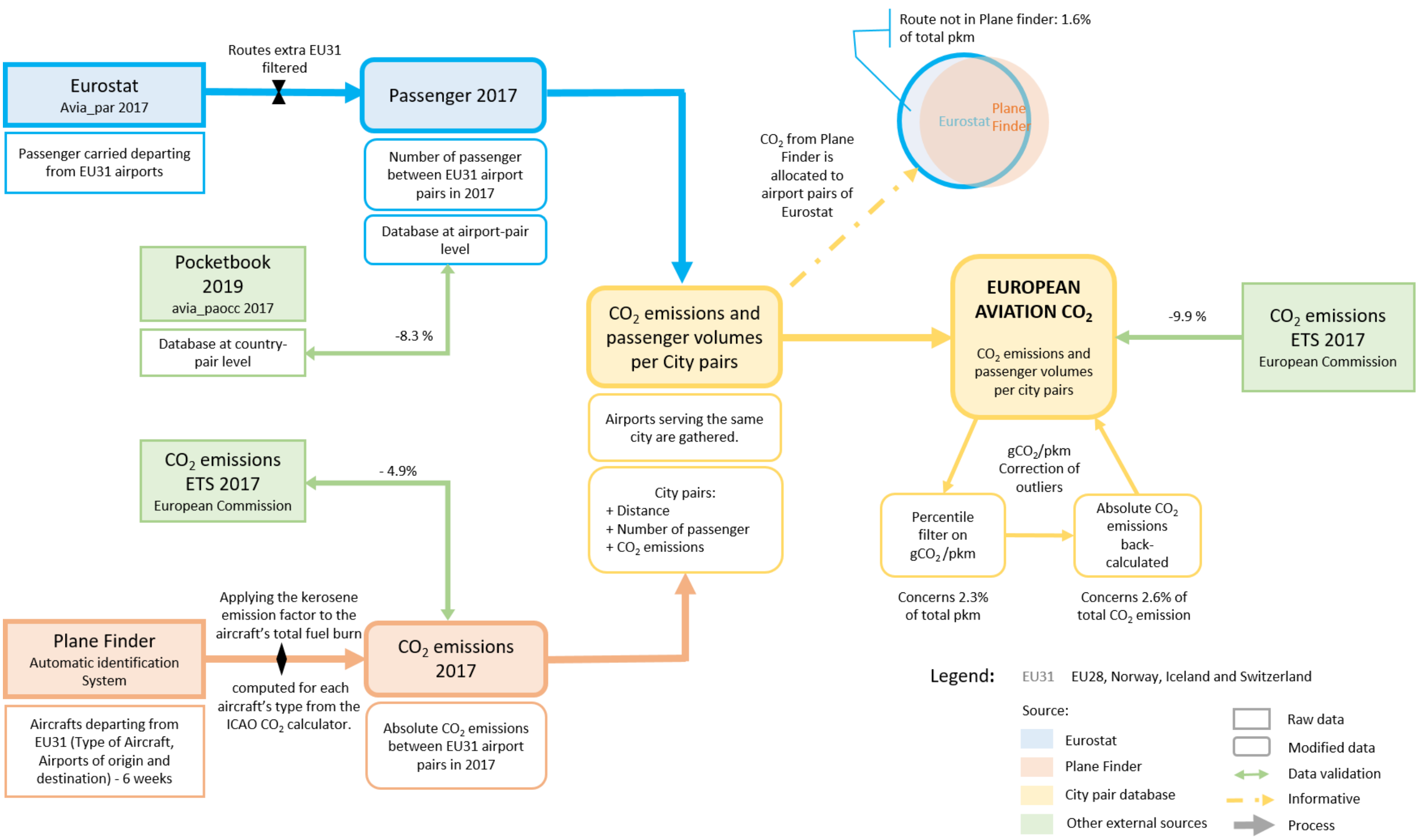

Diagram of the methodology of the European Aviation CO_2 database.

Sources

Passenger flight

- Eurostat, *avia_par* : https://ec.europa.eu/eurostat/data/database
  Detailed air passenger transport by reporting country and routes, 2017.
  Ex: Belgium, *avia_par_be*: Air passenger transport between the main airports of Belgium and their main partner airports.

The complete data set provides passenger volumes of all routes between European airports and their destinations, including those to other continents. The routes have been filtered to keep only the routes within the EU 28, Norway, Iceland and Switzerland (EU31). As Eurostat provides data for single leg (e.g. London Heathrow to Madrid Barajas), the number of passengers of the 2 single legs of a same route were aggregated (e.g. London Heathrow to Madrid Barajas and Madrid Barajas to London Heathrow). In order to get the demand between cities and not airports, airports of a same city were gathered as explained in section City Pairs below.
The database is a selection of the routes between the "main declaring airports" and their "main partners". The "main declaring airports" are listed in *Annex VI*[24] of the Eurostat metadata. As explained in *Annex XV* of the *Reference Manual on Air Transport Statistics*[25], a threshold based on the number of passengers is applied to select the "main partners" of a reporting airport, as follows.

Annual data

Classes	Threshold (passengers)
[150 000 ; 300 000[	10 000
[300 000 ; 1 000 000[	15 000
[1 000 000 ; 5 000 000[	20 000
[5 000 0000 ; 10 000 000[	40 000
[10 000 000 ; + [	75 000

For example, for airports with a number of passengers between 150 000 and 300 000, the routes with more than 10 000 passengers are selected. It was estimated that the threshold results in a lack of 8.3% of passengers, compared to the dataset at country pairs level[26]. Since the threshold applies on the smallest routes, it was considered that the passenger demand remains well depicted.

[24] https://ec.europa.eu/eurostat/cache/metadata/en/avia_pa_esms.htm#annex1574073765603
Some European outermost regions have reporting airports. They are nine: Canary Islands (Spain), French Guiana (France), Guadeloupe (France), Martinique (France), Mayotte (France), La Réunion (France), Saint-Martin (France), Azores (Portugal), Madeira (Portugal). The database allows the user to exclude them from the calculations.
[25] https://ec.europa.eu/eurostat/documents/29567/3217334/Aviation+Reference+Manual+%28version+14%29/e2d532c6-a54a-465a-95e0-f62b76e7da4c
[26] Statistical Pocketbook 2019, EU Transport in figures. Air – passenger traffic between member states (Source Eurostat *avia_paocc*)

CO_2 Emissions from Air Travel

- Flight tracking Service Plane Finder, *Automatic Identification System (AIS)* for flights departing from EU31- Provides Aircraft Type, Origin and Destination airports.
  Data for 6 weeks – first week of November 2016, February 2017, July 2017, August 2017, November 2017, and February 2018.

The amount of CO_2 emitted by each Eurostat route in the studied weeks is calculated by applying the kerosene CO_2 emission factor to the aircraft's total fuel burn, computed for each aircraft's type from the ICAO CO_2 calculator[27]. The weekly data are extrapolated to get annual absolute CO_2 emissions[28]. CO_2 emissions calculated from Plane Finder were found 4.9% smaller than verified emissions from ETS scope[29]. It can be explained by the fact that some seasonal flights were not operated during the studied weeks, no distance was added between city pairs to account for detours, or that, even if fuel consumption was calculated by types of aircraft (e.g. A320), the model was not taken into account (e.g. A320neo).

Distances

Distances were calculated as the great circle between two points, based on the coordinates of the airports.

Allocating absolute CO_2 emissions from Plane Finder to Eurostat routes

Eurostat routes that are not available in Plane Finder data are allocated CO_2 emissions calculated under the assumption that half of aircraft are A320 and half are B738[30]. It concerns less than 2% (1.6%) of total passenger-kilometres. As mentioned below, a reason is that some seasonal flights may not appear on the analysed weeks. Plane Finder routes that are not in Eurostat are not investigated further.

As a check, we investigated the gCO_2/pkm, to verify the consistency of the two different datasets – absolute CO_2 emissions being drawn from plane Finder and passenger volumes from Eurostat. We found some outliers resulting from combining the two sources; they were corrected by applying a percentile filter: values of CO_2 per passenger-kilometre below the 5^{th} percentile or above the 95^{th} percentile were brought back to the average value, weighted by passenger number, of the corresponding distance band. CO_2 emissions are then back calculated from the corrected gCO_2/pkm, based on passenger volumes and distances. Among all CO_2 emissions, 2.6% of them result from corrected gCO_2/pkm. The final database CO_2 emissions of the ETS scope are 9.9% smaller than verified

[27] ICAO CO_2 Calculator Methodology, available: https://www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v10-2017.pdf

[28] CO_2 emissions from the 6 studied weeks were weighted in order to approximate emissions of the 52 weeks of 2017.

[29] European Commission, Verified Emissions from aircraft operators, 2017, https://ec.europa.eu/clima/news/emissions-trading-emissions-have-decreased-39-2018_en

[30] Half of the aircrafts were considered as A320, the other half being B738, with typical seat number of 164 and 162, with a load factor of 80%.

emissions[31] (58.0 Mt compared to 64.4 Mt). This is largely explained by the limitation of the Eurostat scope at airport-to-airport level as explained in the paragraph Passenger Flight above. This is considered as a limitation of the database.

The following table summarizes the total of CO_2 emissions for different scopes and external sources.

Scope	European Aviation CO_2 Database (Mt)	Source of Comparison	Mt	difference
Intra EU-31 (including outermost regions)	72.2	-	-	-
EU-31 domestic	15.0	UNFCCC, 2017 [32]	17.6	-14.8%
EU-31 domestic	15.0	ICCT, 2018 [33]	16.4	- 8.7%
ETS (EU-27 without outermost regions plus the UK, Norway and Iceland)	58.0	EC, 2017 [34]	64.4	- 9.9 %

The bigger difference of domestic emissions (14.8%) compared to emissions from the ETS scope (9.9%) can be explained by the fact that small domestic routes are more likely to fall under the threshold of Eurostat, as well as be concerned with seasonal flights.

[31] European Commission, Verified Emissions from aircraft operators, 2017, https://ec.europa.eu/clima/news/emissions-trading-emissions-have-decreased-39-2018_en

[32] UNFCCC, National Inventory Submissions 2017
CO2 emissions from domestic aviation
https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/submissions/national-inventory-submissions-2017

[33] ICCT, CO2 Emissions from commercial Aviation, 2018
https://theicct.org/sites/default/files/publications/ICCT_CO2-commercl-aviation-2018_20190918.pdf

[34] European Commission, Verified Emissions from aircraft operators, 2017
https://ec.europa.eu/clima/news/emissions-trading-emissions-have-decreased-39-2018_en

City Pairs

The following table shows how airports were grouped as part of a same city.

City	Airports
Brussels	Brussels Airport (BRU) Brussels South Charleroi Airport (CRL)
Hamburg	Hamburg Airport (HAM) Hamburg Finkenwerder Airport (XFW)
Berlin	Berlin-Tegel International Airport (TXL) Berlin-Schönefeld International Airport (SXF)
Belfast	Belfast International Airport (BFS) George Best Belfast (BHD)
Nottingham	Nottingham Airport (NQT) East Midlands Airport (EMA)
London	London Gatwick Airport (LGW) London Heathrow Airport (LHR) London City Airport (LCY) London Stansted Airport (SEN) Southend Airport (LTN) London Luton Airport (LTN)
Gothenburg	Gothenburg City Airport (GSE) Gothenburg Landvetter Airport (GOT)
Stockholm	Stockholm Västerås Airport (VST) Stockholm Arlanda Airport (ARN) Stockholm Bromma Airport (BMA)
Tenerife	Tenerife South Airport (TFS) Tenerife Norte Airport (TFN)
Paris	Charles de Gaulle International Airport (CDG) Paris Orly Airport (ORY) Paris Beauvais Tillé Airport (BVA)
Milano	Milano Linate Airport (LIN) Malpensa International Airport (MXP) Il Caravaggio International Airport (BGY)
Rome	Leonardo da Vinci Fiumicino Airport (FCO) Ciampino G.B. Pastine International Airport (CIA)

Annex B – City Pairs Aviation and Railways

Authors : *Juliette Egal, Transport & Environment*
Thomas Earl, Transport & Environment

Based on the model described in Annex A, 72 city pairs were investigated. The selection is a combination of 2 sets of city pairs:

- city pairs between 200km and 800km and more than 1 million air passengers in 2017, from the European Aviation CO_2 Database
- city pairs for which data on rail passenger volumes were available

The following table shows the city pairs ranked by air passengers, along with CO_2 emissions from aviation, rail passengers and a comparison of travel time between the two modes of transport.

City pairs	Distance km	Air passenger 1000	CO_2 emission Air 1000 t	Flight time min	Travel time air min	Rail passenger 1000	Rail time min	Travel time rail min	Comparison Travel time Rail – Flight min
Dublin-London	466	4993	386.3	85	310	X	X	X	X
Amsterdam-London	354	4679	290.4	75	290	540	240	285	-5
Edinburgh-London	535	3432	299.9	90	310	400	270	310	0
Paris-Toulouse	581	3250	215.7	85	285	580	265	310	25
Barcelona-London	1142	3138	324.7	-	-	30	-	-	-
Nice-Paris	681	3080	218.4	90	280	240	420	460	180
Barcelona-Paris	848	2615	220.8	-	-	20	-	-	-
Geneva-London	743	2575	258.4	95	295	-	460	505	210
Glasgow-London	559	2538	219.6	95	300	-	280	320	20
Belfast-London	530	2512	201.8	85	305	-	X	X	X
London-Paris	348	2443	143.7	75	305	2400	140	195	-110
Barcelona-Madrid	483	2342	161.5	80	280	3900	150	185	-95
Madrid-Paris	1047	2338	208.8	-	-	20	-	-	-
Oslo-Trondheim	363	2088	121.2	55	305	839[a]	420	450	145
Berlin-Munich	479	2061	154.9	90	305	340	290	315	10
Rome-Paris	1104	2023	196.2	-	-	40	-	-	-
Catania-Roma	539	2014	149.4	85	315	10	600	645	330
Milano-Paris	625	2003	174.0	95	330	-	450	490	160
Bergen-Oslo	325	1985	108.1	60	260	1177[a]	420	445	185
Berlin-Frankfurt	432	1956	128.6	75	255	500	280	305	50
Barcelona-Palma	202	1945	55.5	55	250	X	X	X	X
Frankfurt-London	647	1936	202.6	100	295	110	390	430	135
London-Zürich	781	1877	207.3	100	305	-	450	495	190
Madrid-Palma	547	1816	120.9	90	285	X	X	X	X
Hamburg-Munich	600	1740	149.1	80	290	200	360	380	90

London-Munich	935	1697	210.7	-	-	40	-	-	-
Berlin-Cologne	465	1658	123.5	75	270	-	260	285	15
Marseille-Paris	638	1632	133.8	85	305	1300	210	260	-45
Athens-Thessaloniki	299	1619	51.7	55	290	-	270	305	15
Oslo-Stavanger	341	1601	98.2	55	245	985[a]	460	485	240
Palermo-Roma	409	1596	100.9	75	300	10	660	705	405
Berlin-Paris	863	1556	109.1	105	320	130	555	595	275
Düsseldorf-Munich	486	1553	133.9	75	275	90	300	325	50
Copenhagen-Oslo	517	1541	132.1	70	260	-	510	555	295
Copenhagen-Stockholm	545	1537	132.9	70	250	-	330	375	125
Bordeaux-Paris	508	1519	110.8	80	300	-	125	180	-120
Lisbon-Madrid	513	1428	110.2	80	290	-	640	665	375
Amsterdam-Paris	402	1421	90.8	85	290	2000[b]	210	250	-40
Frankfurt-Hamburg	412	1395	90.4	65	240	-	230	250	10
Oslo-Stockholm	385	1395	95.0	65	255	-	390	420	165
Gothenburg-Stockholm	389	1332	88.3	60	245	-	210	240	-5
Helsinki-Stockholm	399	1322	79.8	60	250	-	870	895	645
Milano-Roma	474	1309	133.4	75	325	4000	195	240	-85
Malmö-Stockholm	520	1217	84.8	65	275	-	270	295	20
Frankfurt-Vienna	620	1179	107.5	80	280	-	420	450	170
Milano-Naples	663	1178	100.6	80	300	-	280	310	10
Frankfurt-Munich	299	1171	61.5	55	240	-	210	230	-10
Cagliari-Milano	700	1161	102.3	90	305	-	X	X	X
Berlin-Düsseldorf	469	1142	85.9	75	270	-	260	290	20
Barcelona-Milano	742	1134	86.9	100	325	-	750	785	460
Berlin-Zürich	659	1095	96.3	90	280	-	500	530	250
Porto-Lisbon	277	1088	42.7	60	270	-	180	200	-70
Amsterdam-Dublin	750	1088	98.8	100	300	X	X	X	X
Cagliari-Roma	394	1083	72.4	65	280	-	X	X	X
Geneva-Paris	403	1070	65.1	70	260	-	225	265	5
Luleå-Stockholm	689	1064	98.1	80	255	40	360	385	130
Barcelona-Ibiza	276	1059	42.1	65	260	-	X	X	X
Bari-Milano	776	1058	91.3	100	320	-	430	460	140
Amsterdam-Manchester	487	1045	73.2	80	270	-	500	530	260
Munich-Paris	683	1040	90.9	105	325	85	380	415	90
Hamburg-London	730	1038	100.9	100	320	-	610	650	330
Berlin-Stuttgart	517	1037	76.1	75	280	-	340	365	85
Amsterdam-Copenhagen	633	1034	85.4	85	270	-	640	685	415
Dublin-Paris	775	1010	101.1	100	315	-	X	X	X
Lyon-Paris	407	675	36.5	75	290	3400	120	175	-115
Brussels-London	350	651	49.5	80	295	810	120	165	-130
London-Lyon	747	568	53.8	105	330	300	330	390	60
Hamburg-Paris	732	565	44.6	100	310	110	555	590	280

Berlin-Budapest	693	335	35.3	90	305	60	840	870	565
Brussels-Paris	251	186	13.6	60	265	1500	80	120	-145
Rome-Stuttgart	801	112	8.5	100	325	70	750	790	465
Berlin-Hamburg	255	o	-	100	305	1100	105	130	-175

X : No train connection - : Not investigated o : No passenger reported in Eurostat

Data sources

Air Transport:

- Eurostat, *Detailed air passenger transport by reporting country and routes (avia_par)*, 2017. https://ec.europa.eu/eurostat/data/database

Co₂ emissions from air travel

- Analysis of Automatic Identification System (AIS) data from the flight tracking service *Plane Finder* of 6 weeks – first week of November 2016, February, July, August, November of 2017, and February of 2018.

See detailed methodology in Annex A – European Aviation CO_2 Database.

Passenger Rail

- *Compilation of Top Intra-European Flight and Rail Journeys*, Prognos 2017 (unpublished study for T&E)
- (a) Norwegian State Railways, *Personal Communication*
- (b) Kennisinstituut voor Mobiliteitsbeleid (KiM), *Substitutiemogelijkheden van luchtvaart naar spoor*, 2018. https://www.kimnet.nl/publicaties/rapporten/2018/06/21/substitutiemogelijkheden-van-luchtvaart-naar-spoor

Average Travel Times

The average travel times for flights were calculated by summing up:

- The individual flight time (source: scheduled flight times[35])
- The specific time (public transport) to get from city centre A to city Airport A. For cities served by several airports, specific times were weighted by attendance levels of each airport

[35] Scheduled flight times are usually a bit longer than actual times, so that Airlines ensure that they do not have delay and avoid paying a fine.

(e.g. Westminster Station to London Heathrow, London Gatwick, London Luton, London City, London Stansted, and London Southend).

- The specific time needed (public transport) to get from airport B to city centre B. For cities served by several airports, specific times were weighted by attendance levels of each airport (e.g. Paris Orly/ Paris Charles de Gaulle/ Paris-Beauvais to Musée du Louvre).
- And an average duration of stay at both Airport A and B of 120 minutes in total[36] (i.e. check-in, security checks, boarding, baggage drop-off and baggage claim etc.)

The average travel times for rail journeys were calculated by summing up:

- The average time from main station A to main station B (scheduled times)
- The specific time (public transport) needed to get from city centre A to main station A (e.g. Westminster Station to London St. Pancras)
- The specific time (public transport) needed to get from main station B to city centre B (e.g. Paris Gare du Nord to Musée du Louvre)
- And an average duration of stay at the departing station of 10 minutes in total[37] (going to platform, finding the right section etc.)

City centres were defined as a combination of geographical centre and activity centre (e.g Stephan Platz for Vienna).

[36] Kennisinstituut voor Mobiliteitsbeleid (KiM), *Substitutiemogelijkheden van luchtvaart naar spoor*, 2018. https://www.kimnet.nl/publicaties/rapporten/2018/06/21/substitutiemogelijkheden-van-luchtvaart-naar-spoor

[37] Cokasova 2003