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Sleeping our way into replacing short-haul flights – studies of modal shift from short-haul flights to overnight sleeper services

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Abstract

Air transport plays an essential role in Europe's short-haul passenger transport. However, air transport contributed nearly 14% of greenhouse gas emissions of all transport modes in the European Union. Meanwhile, the transport sector must meet the increasing demand for short-haul passenger transport. Based on railway transport's better environmental performance and overnight railway sleeper's advantages on leveraging sleeping hours into efficient travel times, this thesis studies the potential modal shift from short-haul flights to overnight railway sleepers.

By analyzing both the number of passengers for Europe's national and intra-Europe flights and existing overnight sleeper services in and out of Europe, this study flags potential overnight sleeper routes with large passenger volumes and adequate travel distances. The carbon saving potential of these routes has been analyzed in both the short run and long run. In the long run, this study introduces the scenario that synthetic aviation fuels will be adopted in air transport to reduce its environmental impacts.

After a passenger split between overnight sleepers and air transport based on a case study, this study finds that overnight sleepers have negligible carbon reduction effect in the short run. In the long run, with the introduction of synthetic aviation fuels and carbon-free electricity in the transport sector, air transport can reach carbon-neutrality. However, to carry the same number of passengers to various locations, air transport with synthetic fuel will consume 5.9 to 7.7 times more energy than railway transport. Furthermore, air transport's non-CO_2 effects also have global warming potential. Compared with air transport under the synthetic fuels scheme, railway transport shows considerable competitive advantages in energy efficiency and general environmental impact in the long run.

This study concludes that overnight sleepers have shown negligible decarbonization effects in the short run. In the long run, railway transport will have advantages in energy efficiency and environmental impacts over air transport when synthetic aviation fuel is considered. However, overnight sleeper has an upper limit of passenger base because it has a relatively limited travel range. Further studies are needed to plan future short-haul passenger transport modal shift by considering more options, such as high-speed railway.

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Chapter 1 Introduction

In 2017, a total of 1.043 billion passengers used air transport in the 28 European Union Member States (EU28) through around 8 million commercial flights [1]. Figure 1-1 indicates that of the over 1 billion EU28 passengers who traveled by air in 2017, roughly 64% of them traveled intra-EU28. Based on historical data and approximations, each passenger traveled 1070 kilometers per flight, giving a total of 1116 billion passenger-kilometers in 2017 [1-3]. Air traffic is expected to continue its growth in the future [4].

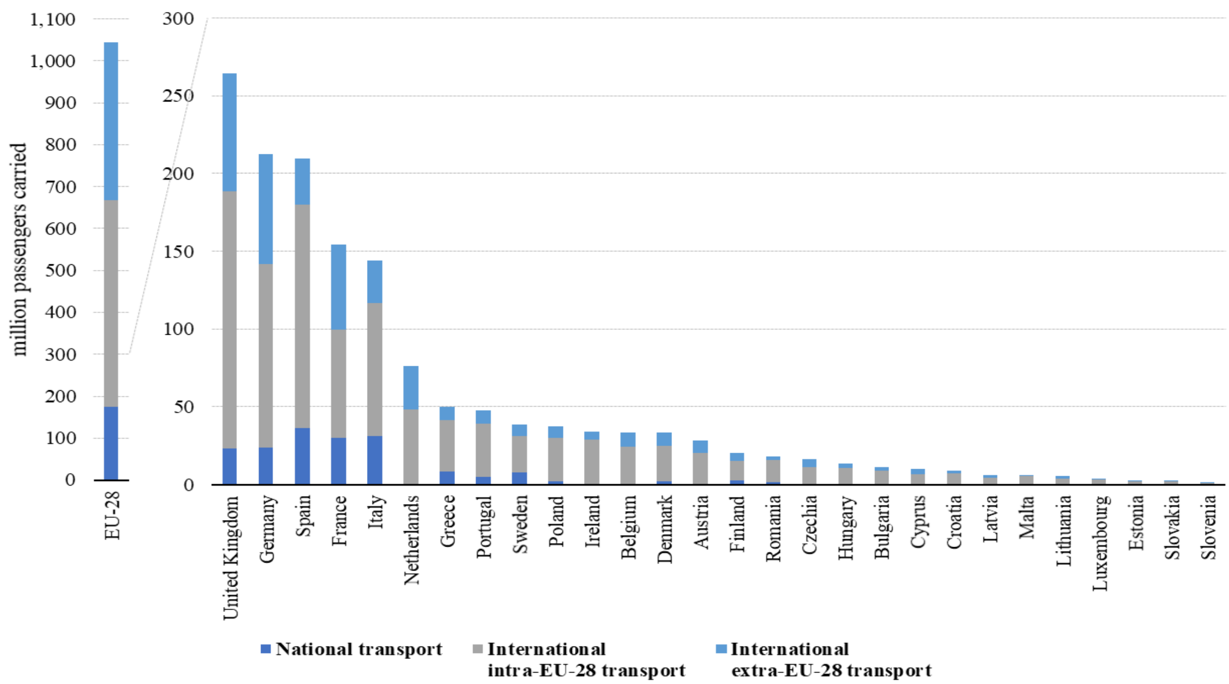


Figure 1-1 Air passenger transport by type of transportation as of 2017 in EU28, modified from [5].

Unlike air transport, which typically covers inter-city travel, railway transport covers different travel types, including short-distance commuting (e.g., S-bahns in Germany, Switzerland, and Austria), mid-/long-distance inter-city transportation, mid-/long-distance high-speed railway, and overnight sleepers.

In the E.U., the total use of railways has been increasing. In 2017, the railway transported more than 480 billion passenger-kilometers, including all travel types, ranging from regional to international trips [6]. The E.U. can be observed with higher railway traffic volumes over the years, as shown in Figure 1-2. To better define the importance of railway transport in inter-city passenger transportations, I reviewed several annual reports of railway transport operators. ÖBB, the Austrian national railway operator, stated that 38.2% of its total 266 million passengers were traveling long-distance [7]. Deutsche Bahn has stated that 5.7% of its total 2581 million passengers were traveling long-distance in 2018[i]. Deutsche Bahn's long-distance transportation accounted for 42827 million passenger-kilometers, and its regional transit accounted for 54880 million passenger-kilometers, leading to regional and long-distance services at a similar scale in terms of passenger-kilometers despite different magnitudes of passenger volumes [8]. SNCF, The French

[i] The ratio of Deutsche Bahn's regional passengers to Deutsche Bahn's long-distance passengers is 2,433 million passengers to 148 million passengers.

National Railway Company, stated that its long-distance and high-speed railway services transported 27.2 million passengers in 2019. It carried more than 5.3 billion passengers in regional transport, indicating that only 0.5% of its passengers traveled long distances. Nevertheless, on the revenue side, SNCF's long-distance and high-speed railway services contributed 36.3% of its total revenue in the passenger transportation business unit[i] [9]. Although ÖBB, Deutsche Bahn, and SNCF have different disclosure levels on their passenger statistics, their long-distance services contributed to high passenger-kilometers. Hence, I conclude that the railway is also an essential mode of inter-city passenger transport in Europe and contributes a substantial share of revenues to Europe's major railway operators.

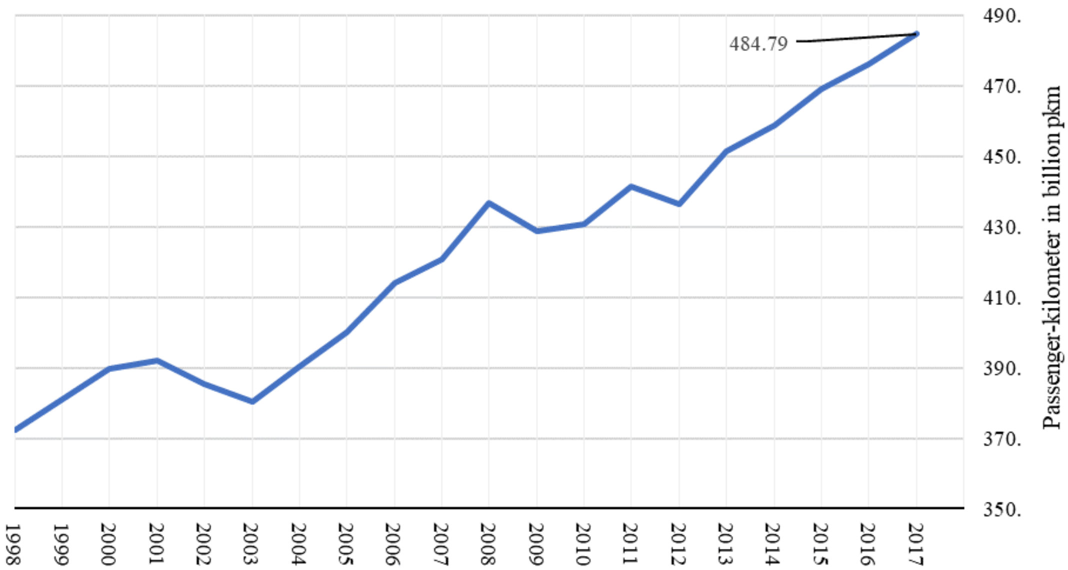


Figure 1-2 Passenger-kilometer of railway transport in all 27 member states of the European Union[ii], modified from [6]. It should be noted that the chart is based on a fixed list of countries, which belong to the E.U.'s member states as of August 2020.

While both the air and railway contributed hugely to inter-city short-haul[iii] travel, they also caused immense carbon emissions. The E.U. aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions [10]. In the transport sector, the European Green Deal plans to roll out cleaner, cheaper and healthier forms of private and public transport sectors and seek a 90% reduction in these emissions by 2050 [11]. Europe must reduce transport emissions further and faster as the entire transport sector accounts for a quarter of the Union's greenhouse gas emissions [12].

[i] SNCF's mass transit had a revenue of 14.2 billion euros, and SNCF's long-distance and high-speed railway services had a revenue of 8.1 billion euros, both in 2019.
[ii] EU28 became EU27 because of Brexit on 31 January 2020.
[iii] In this study's following contents, short-haul specifically refers to short-haul air transport or railway transport with the equivalent distance.

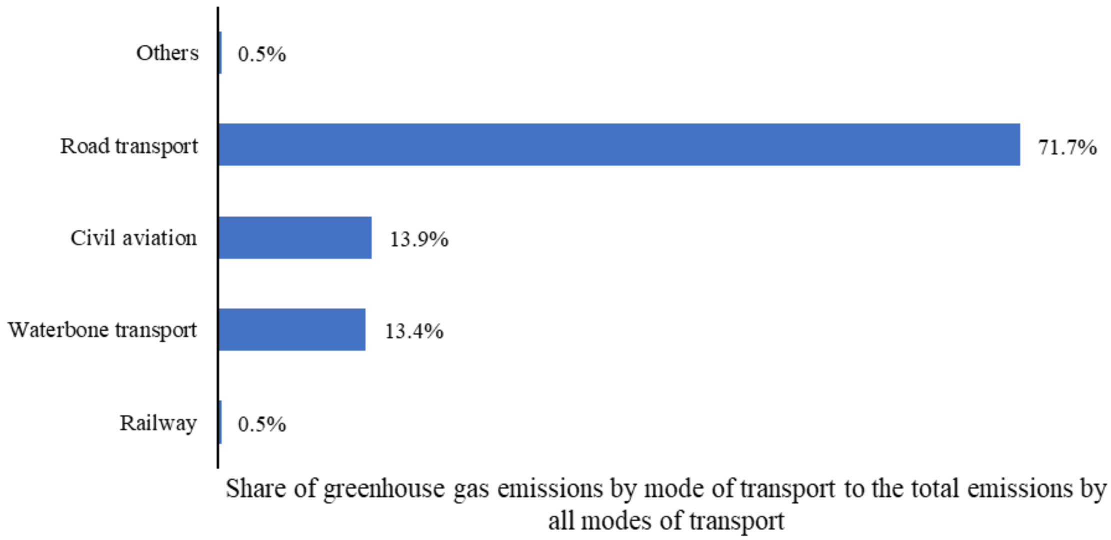


Figure 1-3 Share of greenhouse gas emissions by mode of transport as of 2017 in the E.U., modified from [12].

On the Europe-wide strategic level, the determination to decarbonize the transportation sector is clear. As shown in Figure 1-3, different modes of transport have different shares of greenhouse gas emissions. Different modes of transport and their associated organizations also echo the decarbonization goal with various approaches. Among short-haul passenger transport, civil aviation had higher greenhouse gas emissions than the railway. Detailed literature research and analysis also suggested that air transport has higher CO_2 emissions despite that current aircrafts are 80% more fuel-efficient per passenger-kilometer than the first jets in the 1960s [13]. Flights produced 915 million metric tons of CO_2 to transport 4.5 billion passengers in 2019 worldwide, another 20 million metric tons of CO_2 and 0.2 billion passengers increase compared to that of 2018 [14, 15]. Several sources supported the derivations of CO_2 emissions emitted from air transport within Europe. The exact numbers vary, but the magnitude of CO_2 emissions generated from air transport is consistent. The results from different estimation methods and publications are presented in Table 1-1. In the long run, the European Commission has initiated assessments on alternative air fuels, such as ReFuel-EU, for better abatement of CO_2 emissions from air transport. At the most optimal cases, flights with alternative fuels will be carbon-neutral. However, the production efficiency and non-CO_2 impacts are still needed to be evaluated [16].

Sources	**CO_2 emissions**
Self-calculation method 1 – data of 2017 [1-3, 12, 17-19]	163 g CO_2 per passenger-kilometer
Self-calculation method 2 – data of 2018 [1-3, 5, 15]	121 g per passenger-kilometer
Self-calculation method 3 – data of 2018 [1-3, 20]	154 g per passenger-kilometer
Publication 1 – data of 2011 [21]	~115 g per passenger-kilometer
Publication 2 – data of 2018 [22]	86 g per passenger-kilometer (Intra-Europe flights)
Publication 3 – data of 2011 [23]	164 g per passenger-kilometer (European aviation)
European Environment Agency – data of 2014 [24]	244 g per passenger-kilometer

Table 1-1 Summary of air transport's CO_2 emissions per passenger-kilometers through different studies. The average CO_2 emissions for air is 149.6 g per passenger-kilometer. Descriptions of self-calculation method 1 to 3 are presented in the Method Description 1 to Method Description 3 in Appendix – Descriptions of analysis.

Railway transport has less CO_2 emissions per passenger-kilometer, and Europe's railway transport will be even more emissions-efficient by the pushes of different policies. The E.U. aims to maximize the deployment of renewables and electricity to fully decarbonize Europe's energy supply. Combined with other initiatives, such as maximizing energy efficiency and adapting carbon capture and storage, the European Commission is targeting for a carbon-neutral Europe [25]. With the trend that Europe-wide railways are increasingly electrified, and the production of electricity produces fewer greenhouse gases in the E.U., it is expected that electricity-driven trains will be a transportation mode with low emissions.

Sources	**CO_2 emissions**
Self-calculation method 1 – data of 2017 [6, 12]	13.5 g per passenger-kilometer
Publication 1 – data of 2011 [21]	~41 g per passenger-kilometer
Publication 2 – data of 2008 [23]	11 g per passenger-kilometer
Publication 3 – data of 2016 [26]	44.5 g per passenger-kilometer[i]
European Environment Agency – data of 2014 [24]	28.4 g per passenger-kilometer

Table 1-2 Summary of railway transport's CO_2 emissions per passenger-kilometers through different studies. The average CO_2 emissions for the railway is 27.7 g per passenger-kilometer. Self-calculation method 1's analysis description is presented in Method Description 4 in Appendix – Descriptions of analysis.

Table 1-2 suggests that railway transport's operating CO_2 emissions range from 11 g to 44.5 g per passenger-kilometer. Compared with the CO_2 emissions per passenger-kilometer from air transport, railway transport is a lower emission mode of transport. In addition, emerging technologies, such as potential high-efficiency hydrogen fuel cells and upgraded energy management systems, are likely to help railway transport reduce its carbon emissions further [27].

Figure 1-4 provides a more intuitive illustration of the comparison of CO_2 emissions by two modes of transport. From the information that I have gathered, I conclude that the railway emit less CO_2 than air transport for the same distance that a passenger travels than air transport. Therefore, I address the modal shift possibility of air transport to railway transport to reduce carbon emissions in this master thesis.

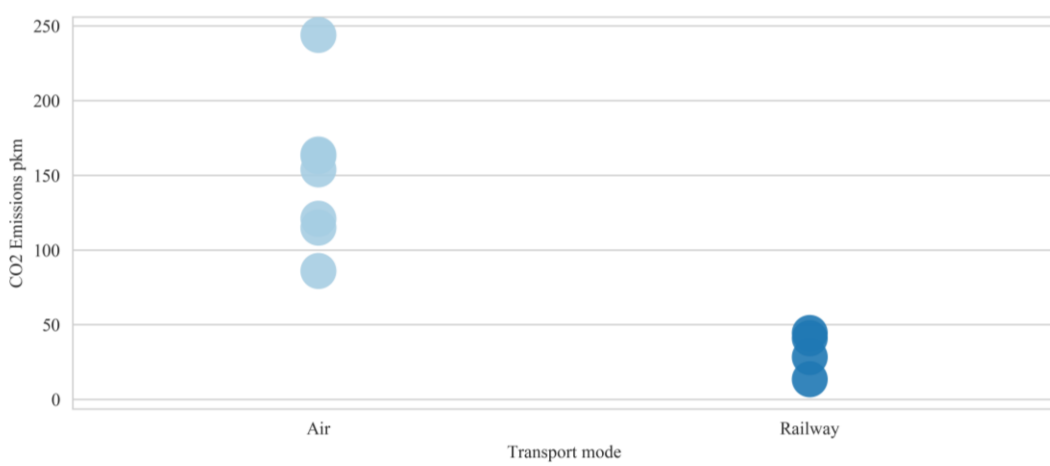
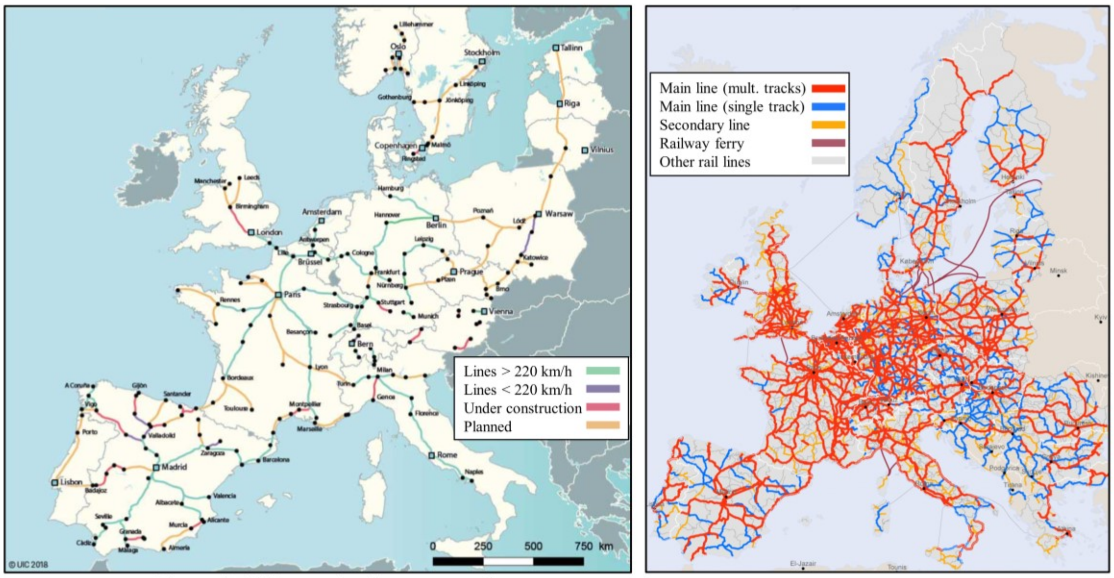


Figure 1-4 Ranges of CO_2 emissions in g per passenger-kilometer by railway and by air. The average CO_2 emissions for the railway is 27.7 g per passenger-kilometer. The average CO_2 emissions for air is 149.6 g per passenger-kilometer.

[i] Result of Rio de Janeiro's regional railway network.

Railway transport has different options for short-haul passenger transport. High-speed railway is a good alternative for air transport for its efficiency with multiple sucessful business cases in Japan, China, and some countries in Europe [28-30]. Europe has a high speed railway network of over 8000 km spanning 11 countries[i], but one key constraint still exists and prevents the high-speed railway as a suitable option to replace air transport. High-speed railway has poor international connectivity [31]. Instances can be found in the France-Germany border, Germany-Denmark border, Swiss-Germany border, and also Swiss-Italy border, as shown in Figure 1-5.



Europe's high speed railway network (incl. under construction & planned)

Europe's normal speed railway network

Figure 1-5 The map of the European high-speed rail network as of 2018 and European railway network as of 2012, modified from [32-34].

On the other hand, Europe's 1435 millimeter standard gauge railway network is relatively well-connected to most urban areas, as shown on the right side of Figure 1-5 [34]. However, normal speed daytime railway services are not a candidate for replacing a part of short-haul flights because of the lack of efficiency in journeys above 500 kilometers. Found examples show that in many inter-city connections, which flights usually take between 1-2 hours, normal speed trains will typically take four to five times of the air travel time, as provided in Appendix Table 1.

Due to the lack of network connections in high-speed railway and the lack of efficiency of normal inter-city trains operating mostly in daytime, I propose that the potential modal shift of using overnight sleepers to replace short-haul flights as overnight sleepers can compensate for the long travel time with traveling overnight.

Many aspects of modal shifts in passenger transport have been studied extensively. In the proposal of using public transport to replace private vehicles, I found various studies that covered different geographical areas researching effective measures to encourage travelers to opt for public transportation, such as local policies and public transport priority systems [35-37].

[i] 11 countries include Austria, Belgium, Germany, Denmark, France, Italy, Netherlands, Poland, Spain, Sweden, and the United Kingdom.

Many studies also covered modal shifts involving railway transport and air transport. Studies have proposed that the modal shift from the road and air to the electrified railway can reduce air pollution. Simultaneously, the transition requires massive investments in building and maintaining infrastructures and may raise noise issues in certain areas [38]. If the environmental impact assessment for railway's modal shift only considers carbon footprints, studies have shown firm conclusions that modal shift from road to rail can result in quantifiable ecological and human health benefits [39-43]. Reviews in various locations on the modal shift from air transport to the high-speed railway are also available. In addition to that high-speed railway has the competitiveness in travel time to air transport, conclusions are very similar that the high-speed railway has shown the environmental benefit over air transport in short-haul passenger transportation [43, 44].

However, the modal shift from air transport to the overnight railway is lacking. As normal speed intercity trains have roughly four times the travel time for the same route compared to airplanes do, I create a new angle of thinking about the modal shift from air transport to the railway by reasoning the potential of using overnight sleepers to replace a portion of existing flight connections.

The research question that guides thorough this study will be the following:

- Can overnight railway sleepers replace some short-haul air transport within Europe in efforts to decarbonize intra-continental travel?
    - What percentage of short-haul flights could be sustainably replaced with railway transport?
    - To what extent can overnight trains aid in the reduction of greenhouse gas emissions in the transportation sector?
    - Under the scenario that railway transport can significantly reduce carbon emissions, how could policy mechanisms and financial tools effectively promote the replacement of short-haul flights with overnight rail travel?

I have structured this thesis as the following to study the proposed modal shift within Europe. Chapter 2 records all the details in data retrieval, data processing, and data visualizations for air passenger transport and overnight railway data. From Chapter 3 to Chapter 5, different topics will be discussed. Chapter 3 will present the visualization results of busy flight routes and current overnight sleeper services. Based on observations, the proposal of new overnight sleeper services and overnight sleeper's current opportunities will be discussed in Chapter 4. Chapter 5 will discuss short-haul transport scenarios in the long run, where I focus on discussing the long-term competitive landscape between railway transport and air transport in short-haul passenger transport. Chapter 6 will wrap up this study with conclusions and future works.

Chapter 2 Data and visualizations

This chapter presents how I gathered, processed, and visualized data for air passenger transport and available overnight railway services in Europe. Section 2.1 and Section 2.2 describe the approaches to handle flight data. Section 2.3 describes the data of overnight sleeper services, and Section 2.4 shows how I made the connection between railway and flight data. In the last section, I will describe issues that I encountered with their solutions.

Section 2.1 Data processing of Eurostat's flight data

This section aims to sort out the flight routes in Europe and provides the basis for analyzing potential routes that overnight sleepers can be deployed.

Subsec. 2.1.1 Procedures for cleaning and aligning Eurostat's data

Eurostat has a comprehensive database storing the historical passenger data of flights [45]. For this study, the specific dataset that I acquired is named "*Detailed air passenger transport by reporting country and routes (avia_par)*". The data was collected by the number of passengers on each flight route. I took the variable in the data named "*Passengers carried (departures)*", which records the number of passengers in each flight route's outbound direction. The purpose of choosing this variable is to avoid double-counting the number of passengers for each route. For instance, Switzerland recorded the number of passengers from Zurich to London, and the United Kingdom registered the number of passengers from London to Zurich. The number of passengers in the corridor between Zurich and London equals the sum of passengers carried in both directions. I mainly use the data of 2019's passenger statistics. The structure of data extracted from Eurostat is shown in Table 2-1.

I applied several steps in the data to clean up the data for further analysis. Figure 2-1 summarizes the general workflow for data processing. Detailed description is presented in Method Description 5 in Appendix – Descriptions of analysis. As the data has inconsistent formatting from country to country, and many manual manipulations were expected, I chose to use Microsoft Office Excel to clean up the data.

AIRP_PR/TIME	Origin Country	2015	2016	2017	2018	2019
BELFAST/ALDERGROVE airport - LANZAROTE airport	the United Kingdom	38,189	54,644	62,133	66,182	55,339
BELFAST/ALDERGROVE airport - TENERIFE SUR/REINA SOFIA airport	the United Kingdom	37,966	45,708	63,373	65,414	61,479
BELFAST/ALDERGROVE airport - ALICANTE airport	the United Kingdom	57,712	77,271	114,830	122,181	123,165
BELFAST/ALDERGROVE airport - BARCELONA/EL PRAT airport	the United Kingdom	:	:	:	:	:
BELFAST/ALDERGROVE airport - PARIS-CHARLES DE GAULLE airport	the United Kingdom	38,764	38,286	38,690	44,520	45,009

Table 2-1 Sample data retrieved from Eurostat's "*Detailed air passenger transport by reporting country and routes (avia_par)*" dataset. Columns 3 to 7 provide annual numbers of passengers departed of each route from 2015 to 2019.

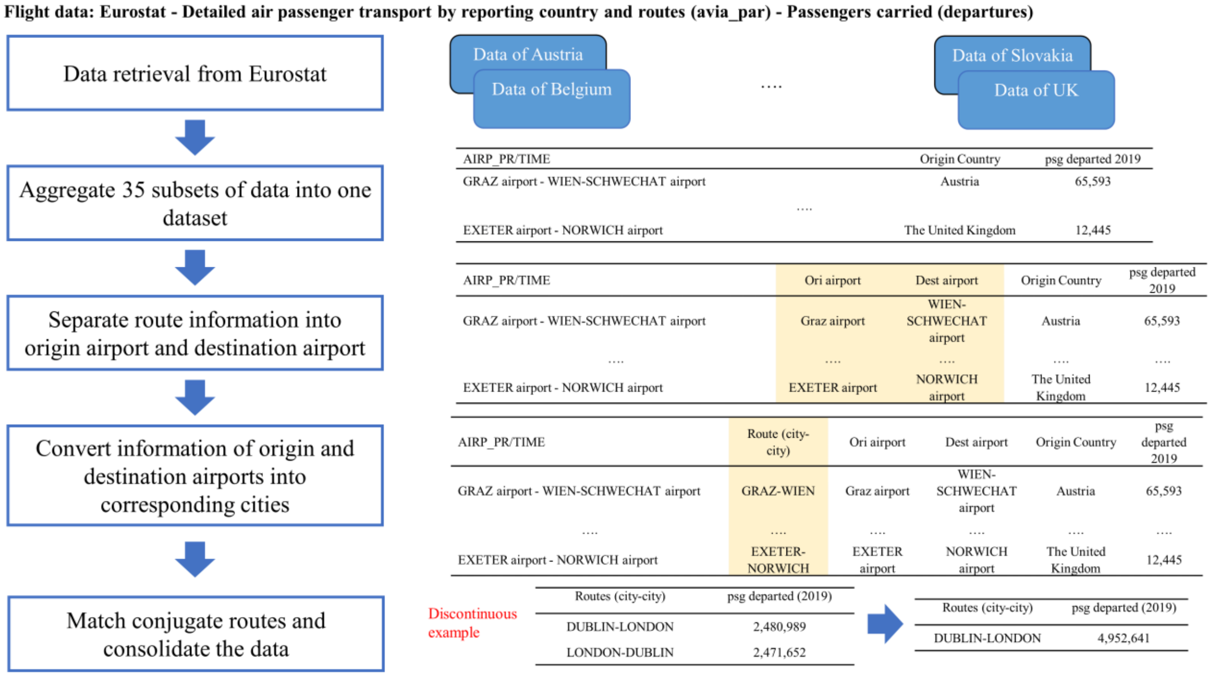


Figure 2-1 Flowchart describing processes of aligning and consolidating flight data. The right side presents the sample results after completing corresponding procedures, as described on the left. Yellow shades indicate new content to the data. Procedure five exhibits a discontinuous example.

The data validation is done by comparing the total passenger volume of the consolidated data with the total number of passengers provided by Eurostat, which indicated that less than 700 million passengers traveled by air within EU-28, as shown in Figure 1-1. My consolidated dataset has the same magnitude of passenger volume, which is 615 million passengers in 2019, signifying that the consolidated dataset has captured most passenger flows happening intra-Europe.

Among all flights, I have filtered out high-volume flights with several assumptions applied. In 2018, Europe's average seats per departure were 148 [46]. Based on the assumption that average seats per departure did not change in 2019, for a flight route that served 600,000 passengers per year bi-directionally, $\frac{\frac{300,000}{52}}{148} = 39$ flights operated weekly per direction. Assuming that the frequency of flights was consistent throughout the week, roughly 5-6 flights operated daily on each route per direction. Sorting out the processed dataset, I have found 239 intra-Europe routes with numbers of passengers exceeding 600,000 passengers. In total, these 239 routes contributed 281 million passengers.

Subsec. 2.1.2 Adding geolocations to Eurostat's flight data

Geodata is needed to assess the replaceability of flights geographically. Therefore, for the dataset that I have processed in Subsec. 2.1.1, I matched a geolocation dataset to the list of origins and destinations. In this step, I used the database provided by SimpleMaps, a database that was refreshed in December of 2019 with 15 thousand places [47]. A sample overview is presented in Table 2-2.

city	city_ascii	lat	lng	country	iso2	iso3	capital	population	id
Tokyo	Tokyo	35.68	139.75	Japan	J.P.	JPN	primary	35676000	1392685764
New York	New York	40.69	-73.92	United States	US	USA		19354922	1840034016
Mexico City	Mexico City	19.44	-99.13	Mexico	MX	MEX	primary	19028000	1484247881

Table 2-2 A sample data from the SimpleMaps' dataset [47].

I adjusted some *"city_ascii"* entries of the dataset retrieved from SimpleMaps as it stores each city's name in English while Eurostat stores origin and destination information in local languages in which airports are located. For instance, Rome's airport in Eurostat is recorded as "ROMA/FIUMICINO airport," and after the processing, as described in Subsec. 2.1.1, "ROMA" was filtered out instead of "ROME." I manually filtered out the names mismatched and changed in SimpleMaps' dataset with Eurostat's nomenclature.

After adjusting the dataset of SimpleMaps, I matched the geolocations of the origin city and destination city of each route in latitude and longitude. For some cities which were not in SimpleMaps' dataset, I used Google Maps to retrieve the geolocations.

I figured each route's great circle distance, based on Equation 1, with geolocations of the origin and destination [48].

$$\begin{aligned}
&\mathit{Great\ circle\ distance\ between\ 2\ places\ in\ nautical\ miles\ (nm)} \\
&= \operatorname{acos}\left[\left(\sin\left(lat_{place1}\cdot\frac{\pi}{180}\right)\cdot\sin\left(lat_{place2}\cdot\frac{\pi}{180}\right)\right.\right. \\
&+ \cos\left(lat_{place1}\cdot\frac{\pi}{180}\right)\cdot\cos\left(lat_{place2}\cdot\frac{\pi}{180}\right) \\
&\left.\left.\cdot\cos\left(lon_{place2}\cdot\frac{\pi}{180}-lon_{place1}\cdot\frac{\pi}{180}\right)\right)\right]\cdot 3443.8985
\end{aligned}$$

Equation 1, retrieved from [48].

By adding the latitudes and longitudes of each route's origin and destination and the great circle distance between each route's origin and destination, I finished preparing the Eurostat dataset ready for further analysis.

Section 2.2 Visualization of processed flight data

In this section, I describe the processes to visualize flight data.

The processed data, which needs to be visualized, was first exported into comma-separated files (CSV) as I use *Pandas*, a Python package, to process table-structured data. Specifically, origins' latitudes and longitudes, destinations' latitudes and longitudes, and passengers' numbers[i] are the needed variables for visualizing the flight routes.

The basemap for visualizations of flight routes uses Python's 2D plotting library *Matplotlib Basemap* [49]. My source codes to visualize the flight routes were based on available open sources [50]. As *Basemap* and the source lack an appropriately scaled color ramp for line plots based on passenger volumes, I apply a manual color ramp to the map. I set the legend's boundary values according to the number of passengers in the input dataset. Figure 2-2 presents the map produced the source code, described by Pseudocode 1 in Appendix – Pseudocodes.

[i] In my dataset, they are named as *"origin lat", "origin lon", "destination lat", "destination lon",* and *"number of psg"*.

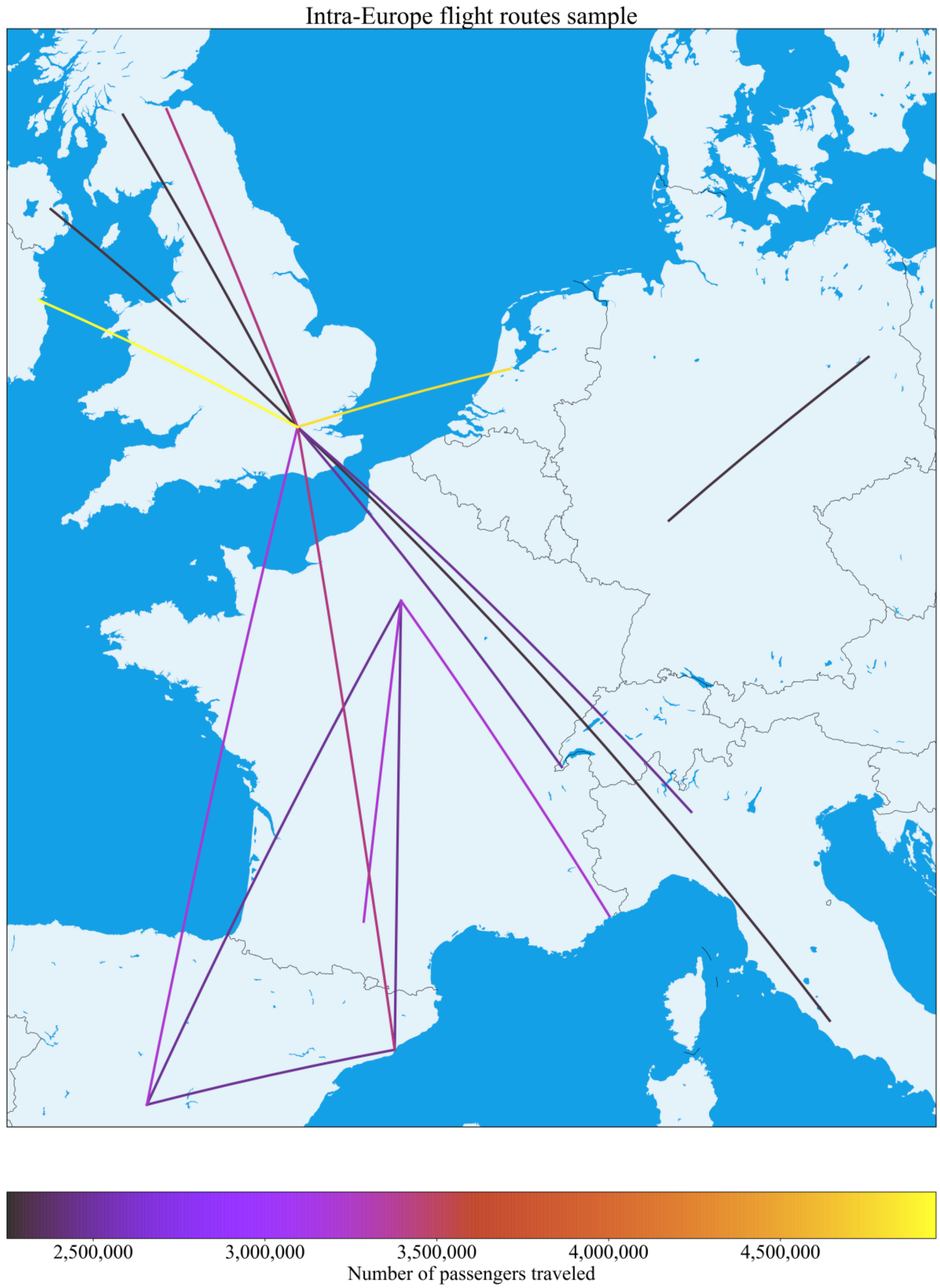


Figure 2-2 The sample figure produced by the Python script, which is described by Pseudocode 1. The projection of the map is Mercator projection (preserving the angles).

With a similar approach, I can also create a scatter map with different colors on the scatters, indicating different intensities. The necessary information to produce a scatter map is latitude, longitude, and passengers' number for each data point. The procedure is shown in Pseudocode 2 in Appendix – Pseudocodes.

Section 2.3 Data for overnight sleepers in Europe

The available overnight sleepers were collected based on desk research from several sources [51-54]. The list of available night train services can be found in Appendix Table 2.

As a dataset of existing overnight sleeper services is not available, and different sources cover different data ranges, I created a data header to store the information of overnight sleeper services. The header is transposed and shown in Table 2-3.

No.	Header name	Description	Sources
1	Trademark/train name	Overnight sleeper's brand name (e.g. Nightjet)	[51-54]
2	Operator	Railway operator (e.g. ÖBB)	[51-54]
3	Covered area	Covered countries	[51-54]
4	Start	City of origin	[51-54]
5	Start_eurostat_name	City of origin complying with Eurostat's storing value	[45]
6	Start Country	Country of origin	[51-54]
7	End	City of destination	[51-54]
8	End_eurostat_name	City of destination complying with Eurostat's storing value	[45]
9	End Country	Country of destination	[51-54]
10	route (city-city)	Route in "city-city" form	=No.5 & No.8
11	corresponding flights	Check if passenger number available in-flight dataset	[45]
12	corresponding psg outbound	match the number of passengers in flight in one direction	[45]
13	Start_geo	Geolocation of origin	[55]
14	End_geo	Geolocation of destination	[55]
15	Duration (h)	Traveling durations based on schedules	[51-54]
16	Distance (km)	Traveling distances based on raildar routing service	[56]
17	Speed (km/h)	Calculated based on duration and distance	=No.16 / No.15

Table 2-3 Header of the dataset for storing the information of available overnight sleepers in Europe.

Some items need to be related to the previous air traffic data in the overnight sleeper dataset, such as Item No. 11 and Item No. 12. After the available overnight services were added to the dataset, I cross-checked whether each overnight sleeper route could match a flight service route. When an overnight sleeper route was found with a corresponding flight route, the number of air passengers was added to the dataset.

By filling up all available overnight sleeper services through desk research, I finished the data collection for overnight sleeper services. In total, I found detailed information on 69 overnight routes. An exemplary overnight sleeper service provider is ÖBB Nightjet. ÖBB Nightjet and its partners served 28 routes as of January 2020 [7, 54, 57]. In 2017 and 2018, Nightjet served 1.4 million and 1.6 million passengers, respectively [58]. Besides ÖBB Nightjet, several other railway companies provide night train services. With the assumption that each route runs bi-directionally, I conclude that 138 overnight services operate daily[i].

Section 2.4 Relating air transport data with railway data

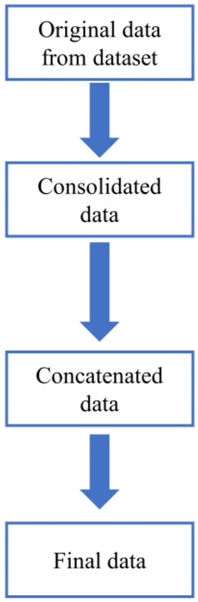
In Section 2.1 and Section 2.2, I have described how the related flight data was processed. For flights travel distance estimation in this study, I assume that flights fly the great circle distance, the shortest distance between two points on a spherical object. As trains do not run perfectly straight lines due to geographical constraints, it is necessary to obtain travel distances of railway transport for each flight route for further correlation studies. Such information will help me determine whether the travel distance of the railway replacement for any flight can be reached within the capability of overnight sleeper services with data support such as the traveling speed of trains.

The methodology of retrieving traveling distance by railway from City A to City B is by rendering geolocations of the origin and destination to raildar.fr, an online railway routing tool, and retrieving the distance [56]. Nevertheless, in Section 2.3, each existing route's distance was retrieved manually as the number of overnight sleeper routes is limited. For retrieving railway distances of flight routes, I deployed a web scraping tool to increase efficiency. The pseudocode of the scraping tool is shown in Pseudocode 3 in Appendix – Pseudocodes.

Subsec. 2.4.1 Estimation of travel times for potential overnight sleeper routes

As the travel time by railway for each flight route is not obtainable through raildar.fr. I need to derive the average traveling speed of currently existing overnight sleeper services as a basis for estimating each route's travel time by overnight sleepers. As the dataset of available overnight sleeper services has calculated each overnight sleeper route's travel times and average speeds, as shown in Table 2-3, the traveling speeds of hypothetical overnight sleeper routes are based on the existing data. For each active overnight sleeper service in the dataset, I had recorded the country of origin and that of destination. I took out columns "Start Country", "End Country", and "Speed (km/h)" from the overnight sleeper service dataset and created two more tables with one table stores "Start Country" and "Speed (km/h)" and another table stores "End Country" and "Speed (km/h)". Then, I consolidated both tables by averaging each country's speed and formed the third table concatenating two consolidated tables. Lastly, I condensed the third table by averaging out each country's entries for traveling speeds. Figure 2-3 presents the flow described above.

[i] In this document, an overnight sleeper route normally indicates bi-directional services. An overnight sleeper service is from City A to City B. An overnight sleeper route indicates City A – City B – City A.



Start Country	Speed (km/h)
Germany	83.4
….	….
Germany	60.1

End Country	Speed (km/h)
Sweden	83.4
….	….
Italy	60.1

Start Country	Speed (km/h)
Austria	73.01
….	….
Greece	44.11

Start Country	Speed (km/h)
Austria	69.01
…	…
Sweden	77.87

Country	Speed (km/h)
Austria	73.01
….	….
Sweden	77.87

Country	Speed (km/h)
Austria	71.00
….	….
Czechia	71.51
Average	71.86

Figure 2-3 Procedure to derive the average speed of overnight sleeper routes by country.

Each flight route's railway travel time is estimated by dividing the railway traveling distance by the average speeds of the countries of origin and destination of the specific course. Under the scenario that countries involved in a flight route do not have overnight sleeper services yet, the average speed derived from all existing overnight sleepers is referenced.

Section 2.5 Issues in data processing

There are two types of issues in the processes described above. First type of issues relates to Eurostat's data. The second type of issues was encountered with the online railway routing tool.

Subsec. 2.5.1 Issues related to Eurostat's data

In Eurostat's data, Czechia did not record the data as the form which most countries did as it only recorded the countries of destinations. After comparing the number of passengers outbound with that of inbound for the entire set of data, I concluded that the average ratio of the number of passengers outbound to that of inbound is very close to one for most routes. Therefore, by assuming that the number of passengers outbound is the same as the number of passengers inbound for all routes involving Czechia, I filtered out all inbound routes from other countries into Czechia firstly and placed the number of passengers outbound from Czechia as the same as the number of passengers inbound to Czechia.

Some routes, which had passengers in both directions, were spotted not recorded realistically in the dataset. For instance, for Graz's service to Zurich, Austria's data provider recorded the number of passengers outbound, but Switzerland's statistics office did not record the inbound statistics. According to Graz Airport, Graz to Zurich was a bi-directional commercial service in 2019 [59].

Subsec. 2.5.2 Issues related to online railway routing tool

For the routing tool, an issue was also observed. I noticed that the distance calculations for certain routes in raildar.fr were inaccurate while validating the railway distance. I found errors by comparing the railway distance with the calculated great circle distance of each route. When the railway distance was less than the great circle distance, I marked the railway distance as an error. After sorting, I found two types of errors in the routing results.

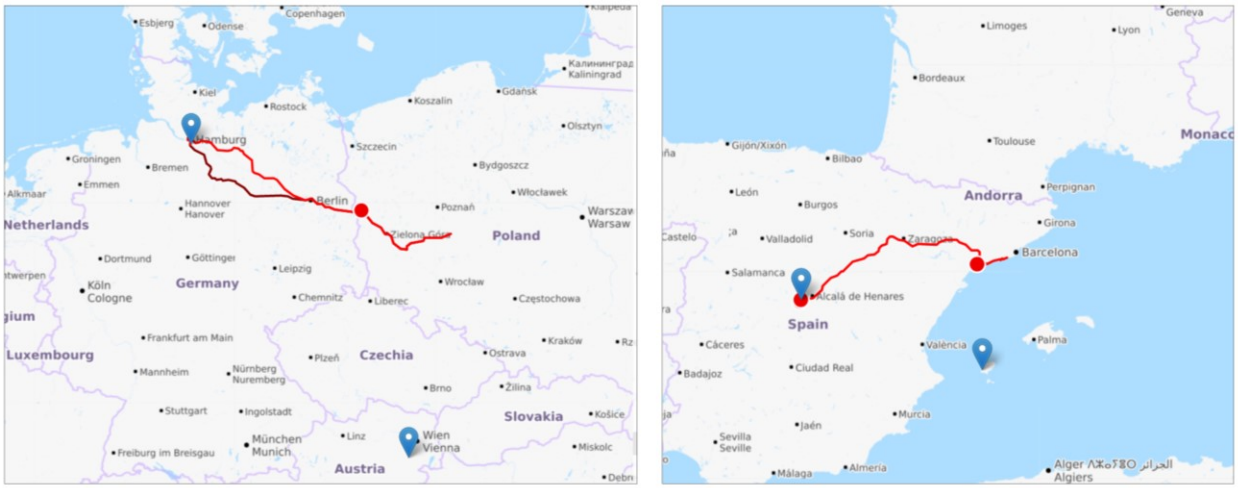


Figure 2-4 Routing errors of raildar.fr for railway routes of Hamburg, Germany to Vienna, Austria (Left), and Madrid, Spain to Ibiza, Spain (Right).

The first type of error was found that distance calculations related to Vienna, Austria, or Malaga, Spain, stop in the middle of the full trip with the origins and destinations are set with right geolocations. An example can be found in Figure 2-4 (Left). To solve such an issue, I manually set the geolocations of the origin and destination for routes found with errors in raildar.fr. The reset geolocations are still near the original origin and destination but without the error observed in raildar.fr.

The second type of error was found that for some routes that are involved with near-continental islands. Such as routing requests to Ibiza, Spain, raildar.fr can still provide an output of non-zero distance. However, Ibiza has no railway connections, as suggested by other routing tools [55]. The instance can be found in Figure 2-4 (Right). The solution to this type of routing error is to set the railway distance of these routes to zero manually.

Chapter 3 Observation of current flights and overnight sleepers

This chapter presents the visualization results of flight routes. In Section 3.1, the visualization of popular flight routes will be presented with observations described in the end. Section 3.2 will draw observations of locations with exceptionally high intra-Europe traffic volumes. Section 3.3 will deliver the visualized results and observations of existing overnight sleeper services on the railway side.

Section 3.1 Maps of flight routes and observations

As described in Section 2.1, I have filtered out 239 high-volume flight routes exceeding 600,000 passengers in 2019. The visualization of 239 routes can be found in Figure 3-1. The reason to filter out these flight routes with exceptionally high passenger volumes is to select the most attractive routes for potential overnight sleepers to be deployed. Such a selection criterion assumes that flight routes with higher passenger volumes are more likely to succeed for overnight sleepers than other flight routes with lower passenger volumes.

Figure 3-1 illustrates that the traffic of air transport in Europe is somewhat asymmetrical. Flight routes exceeding 600,000 passengers operated mostly in Western Europe in 2019. Even several flights involving Eastern European countries, such as flight routes related to Romania and Greece, connect to Western Europe. In this study, Eastern Europe is defined as countries on the east of either Germany, Austria, or Italy's eastern continental borderline, excluding Finland.

Countries like the United Kingdom, Germany, France, Spain, and the Netherlands contribute most of the flights. More specifically, cities like London, Frankfurt am Main, Paris, Madrid, and Amsterdam are observed with multiple busy routes, as shown in Figure 3-1.

Nevertheless, Figure 3-1 is difficult to visually follow the specific routes because many routes are printed on the same map. Therefore, I present routes exceeding 600,000 passengers by region. I split routes into nine categories and deliver them in an aggregated form in Figure 3-2. Detailed high-resolution maps can be found in Appendix – Figures. The split is presented as the following:

- Flight routes involving the United Kingdom and Ireland.
- Flight routes involving France.
- Flight routes involving Belgium and the Netherlands.
- Flight routes involving Germany.
- Flight routes involving Italy.
- Flight routes involving Austria and Switzerland.
- Flight routes involving Spain and Portugal.
- Flight routes involving Nordic countries (incl. Denmark, Norway, Sweden, and Finland).
- Flight routes involving other countries (incl. Poland, Romania, Greece, and other countries not included in the list above).

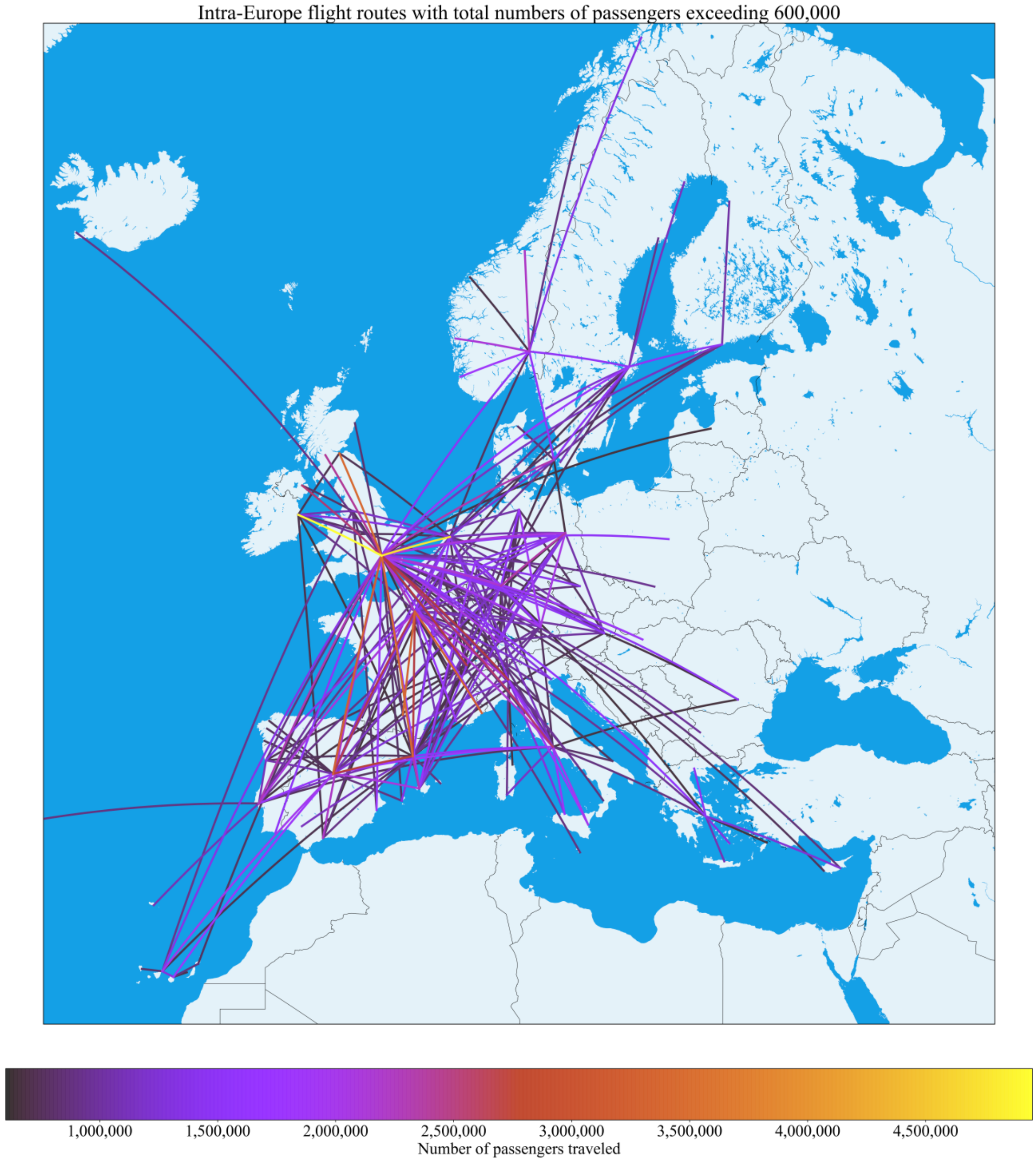


Figure 3-1 Visualization of intra-Europe flight routes with total numbers of passengers exceeding 600,000. The projection of the map is Mercator projection (preserving the angles). The methodology is based on [50].

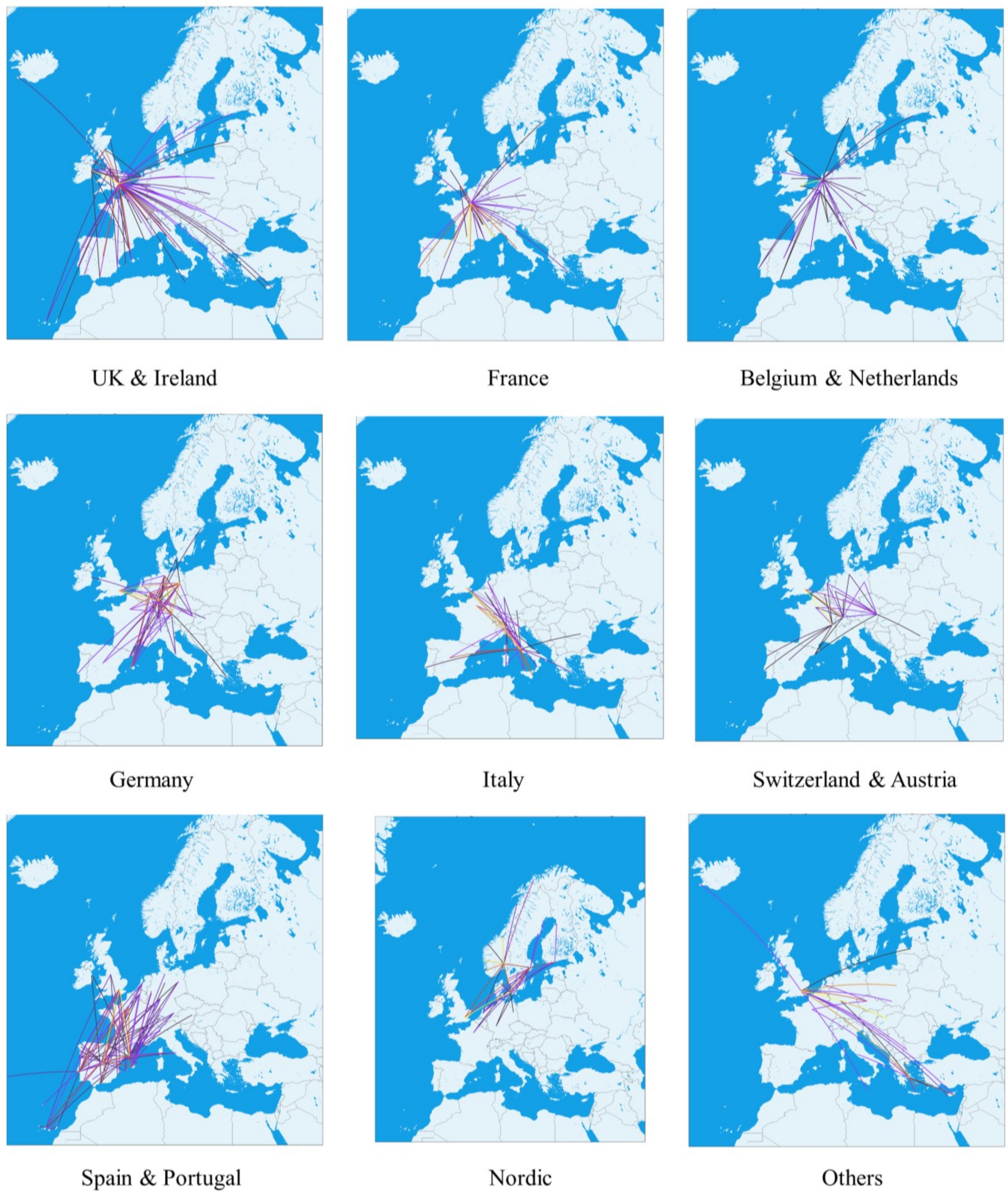


Figure 3-2 Aggregated form of nine maps of popular flight routes by countries. It should be noted that the color scale of each map varies. More information on each map’s color ramp and higher-resolution maps can be found from Appendix Figure 1 to Appendix Figure 9 in Appendix – Figures.

I identify radial patterns as hubs because past studies had revealed that most hub airports showed similar radial patterns and could be categorized as the hub in the hub-and-spoke system [60-62]. London, Paris, and Amsterdam display similar radial patterns. Oslo and Stockholm can also be classified as hubs. They present similar radial patterns but with fewer routes.

I categorize Germany's air passenger transport as a mix of a point-to-point system with a hub-and-spoke system. Internationally, taking London's routes as an example, five routes from Germany to the United Kingdom exceeded 600,000 passengers in 2019. Domestically, Germany has seven airports serving 11 domestic routes, which exceeded 600,000 passengers in 2019. Figure 3-3 presents a schematic and simple view of Germany's 11 domestic routes and five London connections that served more than 600,000 passengers in 2019. I define Germany's air transport model as a hybrid system as each major city directly connects a set of destinations of high traffic volumes without transferring stops, as shown in Figure 3-3. On the other hand, Frankfurt and Munich serve as hubs for destinations with fewer traffic volumes, such as Budapest [61].

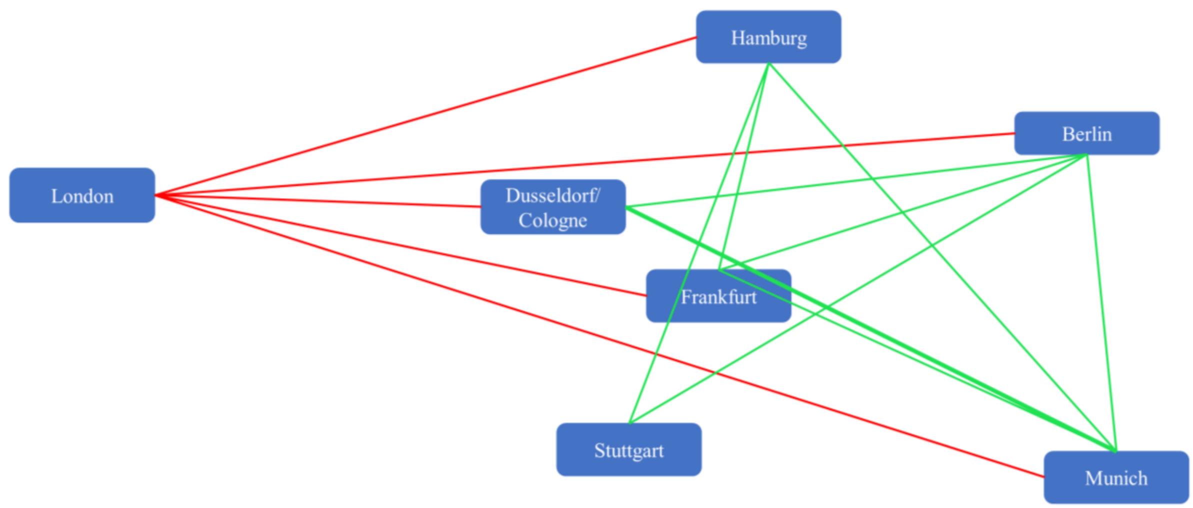


Figure 3-3 Schematic illustration of Germany's point-to-point part of its hybrid system. Green lines indicate domestic routes, and red lines indicate the available connections to London. Munich to Dusseldorf/Cologne is marked in bold line as Munich to Dusseldorf and Munich to Cologne were two routes with more than 600,000 passengers in 2019.

In maps of Spain, Portugal, and Italy, I observed some similarities in flight routes. Figure 3-2 shows that Spain and Portugal's flight routes express a southwestern-to-northeastern trend, and flight routes in Italy express a southeastern-to-northwestern movement. Switzerland, Austria, and Eastern European countries such as Greece and Romania are also observed with a southeastern-to-northwestern trend of flights.

For flight trends of Spain, Portugal, and Italy, a schematic illustration of the observed flight trends is presented in Figure 3-4. I also observe that Spain has three flight sub-trends, the Canary Islands to the Spanish mainland, Ibiza to Germany, and inland of Spain to the United Kingdom. They are all following the southwestern-to-northeastern trends.

I conclude that flight routes in Spain, Portugal, and Italy follow the shape of southern Europe, where the Iberian Peninsula and the Apennine Peninsula form an "A" shape with the western Mediterranean and lead the flight routes operating from southwestern-to-northeastern, southwestern-to-northeastern, and southeastern-to-northwestern, respectively.

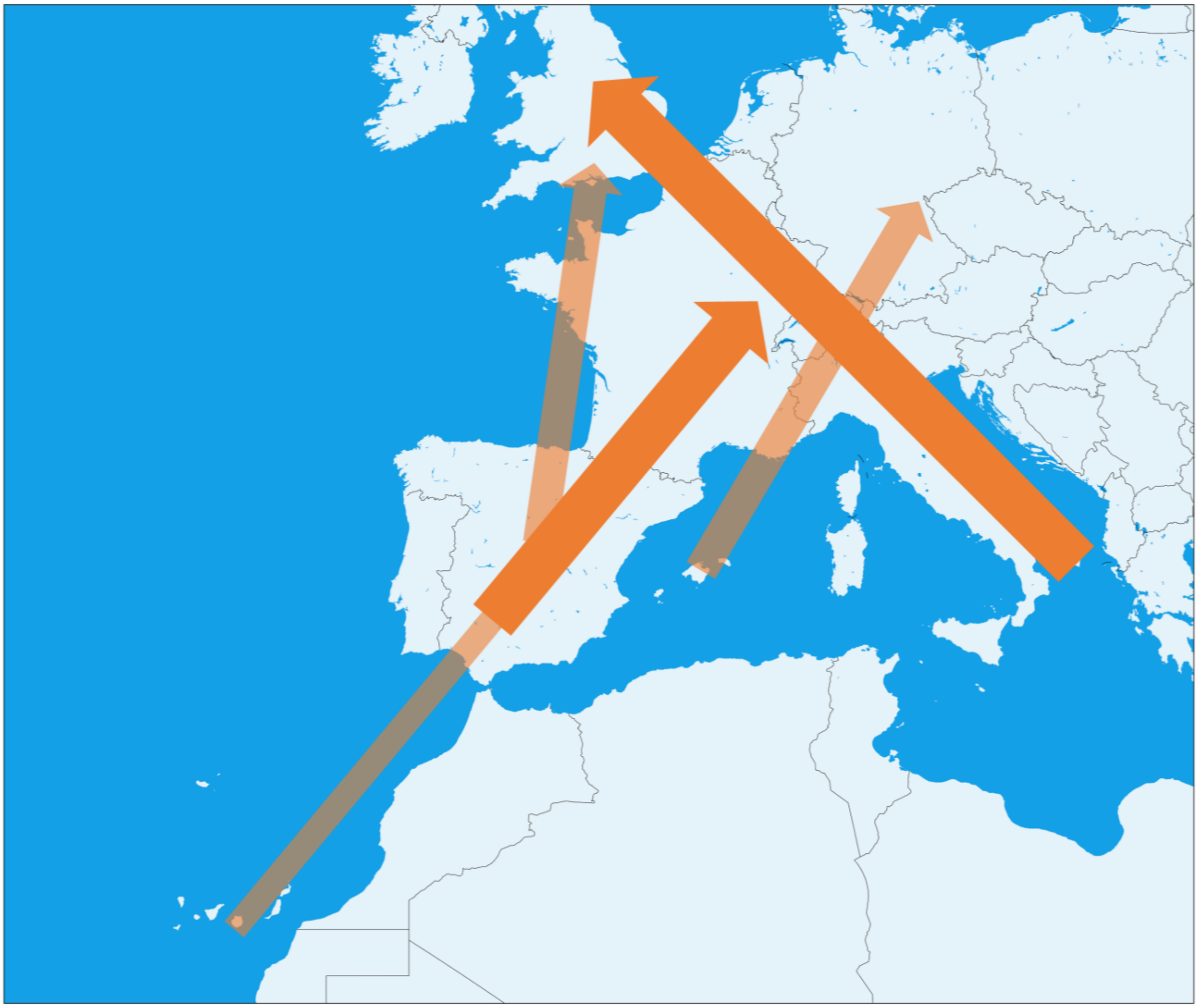


Figure 3-4 Schematic illustration of main flight trends in Spain, Portugal, and Italy observed. Transparent arrows indicate sub-trends, while solid-filled arrows indicate the main flight trends observed.

Figure 3-2 shows that most high-volume flights involving Eastern Europe connect to Western European destinations except domestic flights connecting Greek islands. Therefore, an asymmetry between Western Europe and Eastern Europe is identified.

In conclusion, after I split routes into nine categories for the data of 2019, I categorize four types of flight patterns:

- Radial patterns of the London, Amsterdam, and Paris help me identify them as hubs in the hub-and-spoke system. Oslo and Stockholm are also recognized with similar patterns.
- In Germany, a hybrid of point-to-point and hub-and-spoke systems in domestic routes and some international connections is identified.
- In Italy, Spain, and Portugal, flight routes mostly operated in specific trends following Europe's landscape.
- The asymmetry of high-volume flights between Eastern Europe and Western Europe is very apparent.

Consequentially, in the following study on potential overnight sleeper routes, I expect that potential routes will stress heavily on hubs, especially in the Western Europe. Furthermore, Germany may be found with multiple domestic and international routes, and Southern Europe may be found that potential routes are following the landscapes.

Section 3.2 Hotspots of intra-Europe flight services

In Section 3.1, I have presented the visualization of high-volume flights. A hotspot in this section is defined as a city with an intra-Europe passenger volume of over 10 million. In 2019, 35 hotspots can be identified through my processed dataset. London has the highest intra-Europe passenger volume, which is over 107 million passengers. A significant gap has been identified between the highest and the second-highest hotspots, where Paris had only half of the traffic volume compared to London.

I visualized the processed data by sorting out the busiest hotspots, as shown in Figure 3-5.

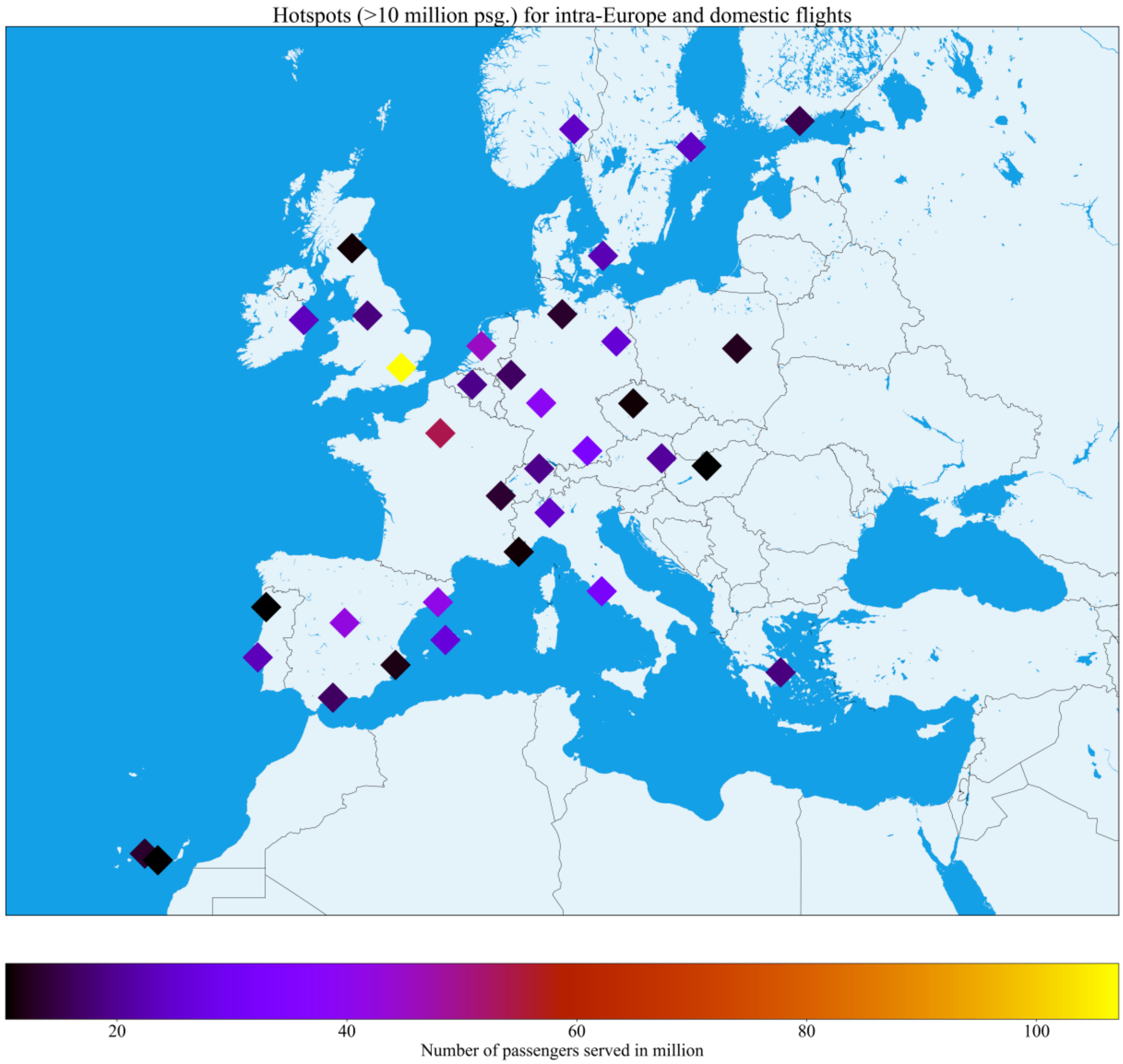


Figure 3-5 Scatter map for intra-Europe flight hotspots.

Observations of Figure 3-5 can accommodate the conclusions made in Section 3.1. For hubs like London, Paris, and Amsterdam, above 40 million passengers per hotspots are identified. Germany has five cities identified as hotspots showing further evidence of the hybrid system. The distribution of hotspots in Spain, Portugal, and Italy shows the same geographical trends as high-volume flights. In Eastern Europe, only four hotspots are identified, while in Western Europe, 31 hotspots are identified. Figure 3-6 can also help identify the asymmetric distribution of flight passengers between Eastern Europe and Western Europe.

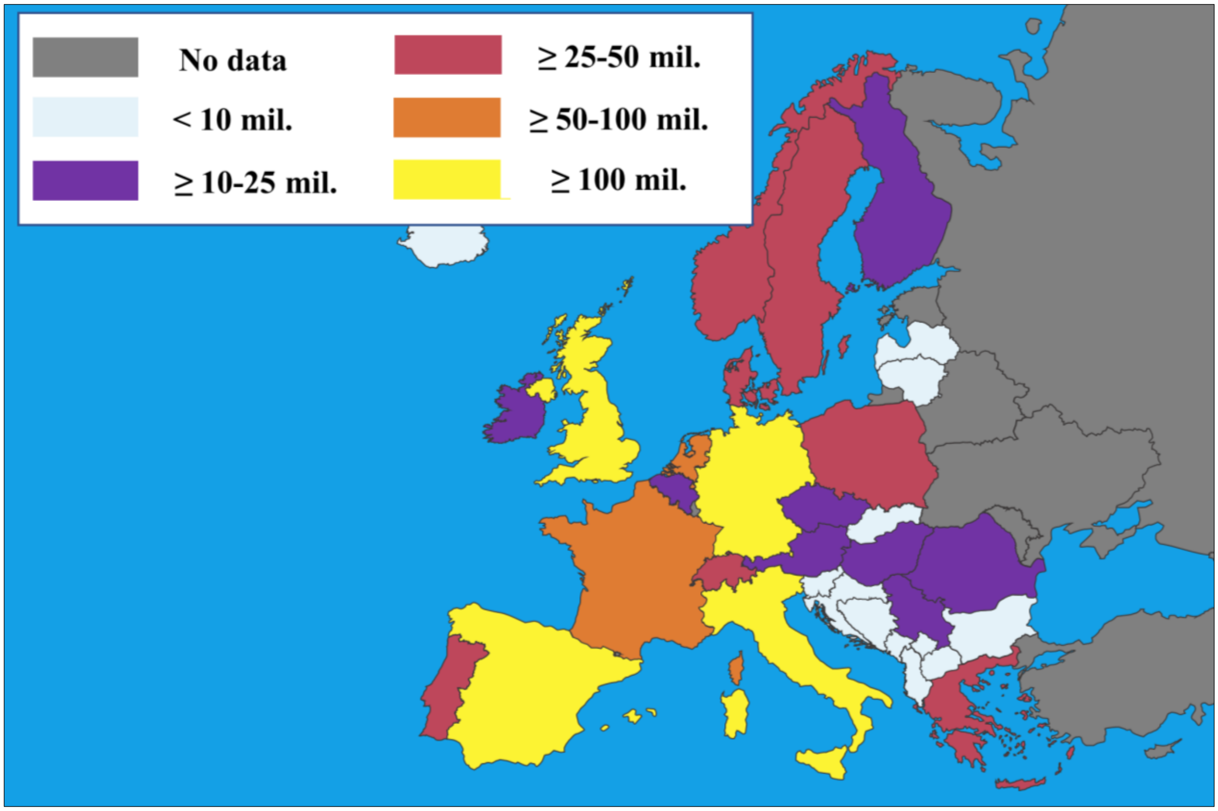


Figure 3-6 Map of Europe's intra-Europe air passenger volume distribution by country.

Section 3.3 Observations of overnight sleeper data

This section will switch the observations from data of flights to data of existing overnight sleeper services. The observations of the overnight sleeper data are based on the data collected by desk research, as described in Section 2.3.

Thanks to Europe's dense railway networks, overnight sleeper services can leverage the existing railway network and technically reach most urban areas in Europe. Currently, more than 60 overnight sleeper routes are operating in Europe. Each overnight route typically runs bi-directional daily. Figure 3-7 shows that more than 100 overnight sleeper services have a duration of fewer than 13 hours. The distribution is slightly left-skewed while the median and the average time are both 12.1 hours.

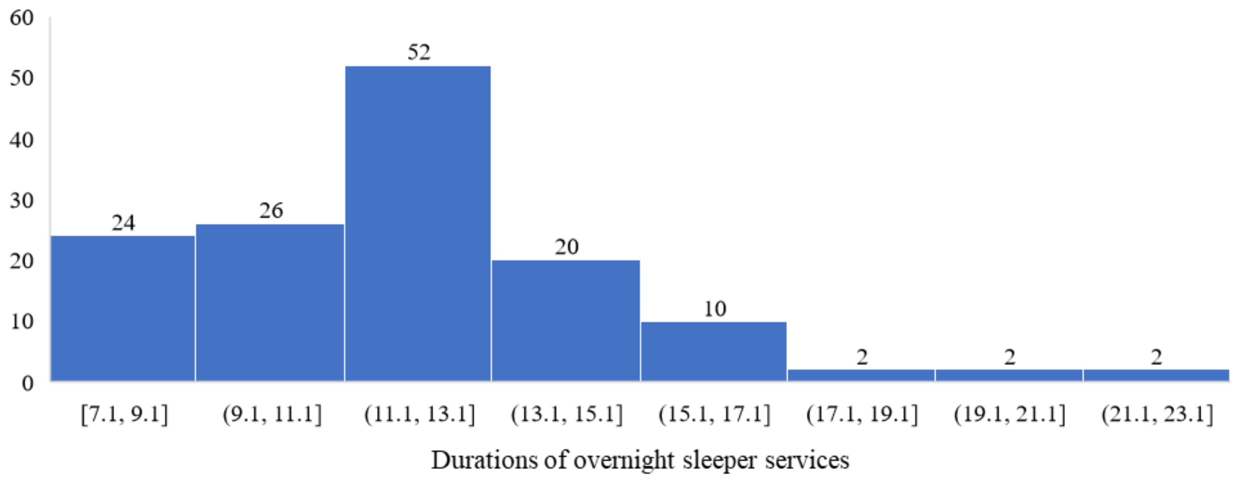


Figure 3-7 Distribution of available European overnight sleeper services' travel times. The median and mean travel times are both 12.1 hours.

Sorting out the departing stations of collected overnight sleepers services, I find that 61 cities serve overnight sleeper service. Cities with more than three services per day are presented in Figure 3-8. As ÖBB's headquarter, Vienna has 11 services per night and is the largest hub for overnight sleeper services. Thanks to Zurich's and Munich's proximity to Austria, they serve 7 and 6 overnight sleeper services, respectively. Rome and Milan overnight sleeper services combine both ÖBB Nightjet's services and Trenitalia's domestic sleeper services. Overnight services involving Paris and London mainly serve domestic services. Cities serving overnight sleepers are somewhat dispersed and irregular. There is hardly a correlation between flight hotspots and overnight hotspots, as shown in Figure 3-9.

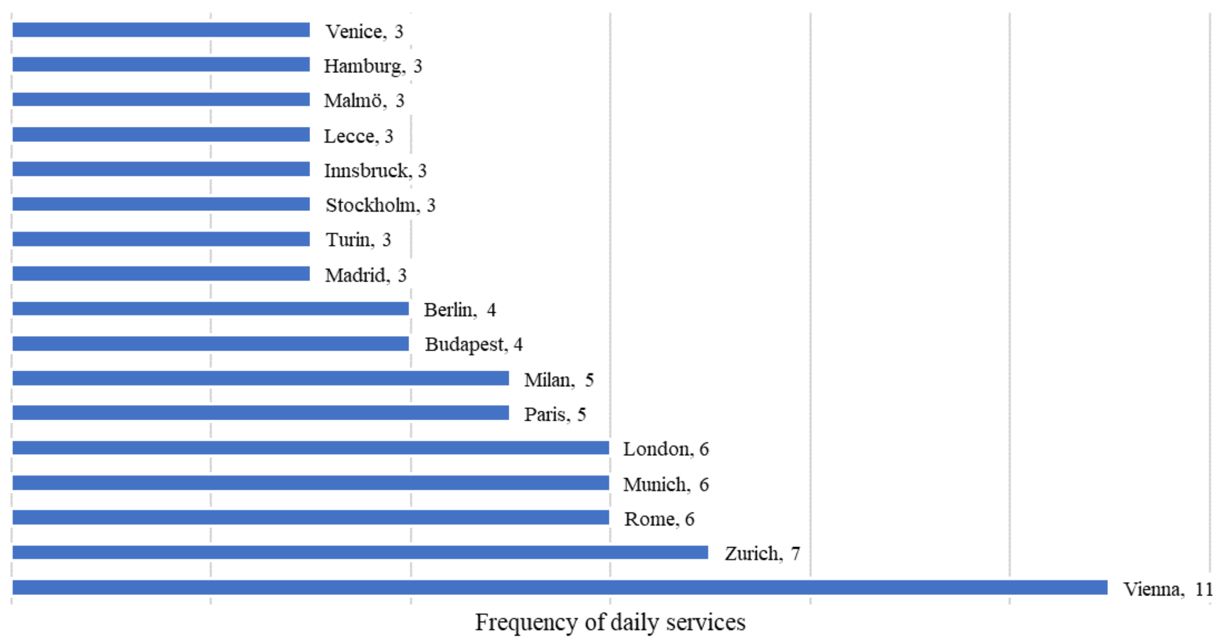


Figure 3-8 Departing cities of existing overnight sleeper services sorted by the number of services. There are 60 services that are associated with cities with no more than two services. These cities are not displayed here.

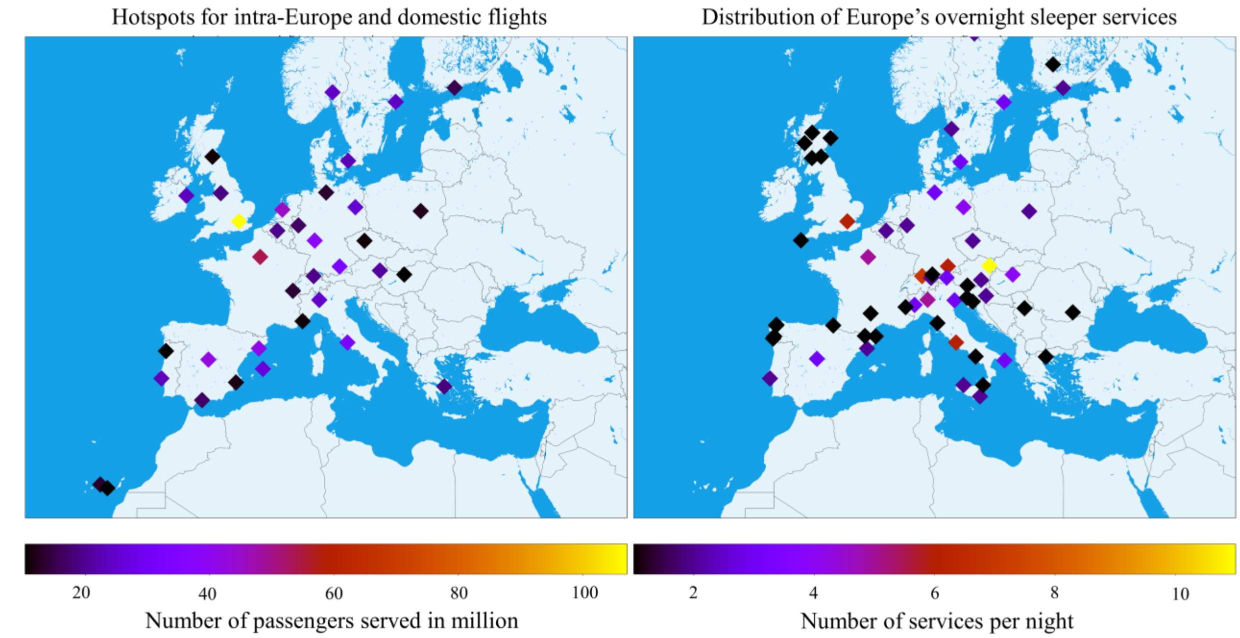


Figure 3-9 Scatter map of intra-Europe flight hotspots versus scatter map of overnight sleeper services by cities. It should be noted that legends have different meanings in two maps.

Figure 3-10 illustrates the distribution of overnight sleeper services in Europe by country. It is observable that Western Europe has the most overnight sleeper services. In Eastern Europe, most of the overnight sleeper services are still operating under EuroNight's brand, associated with ÖBB Nightjet. Compared to the air transport, Europe's overnight sleeper services are relatively sparse.

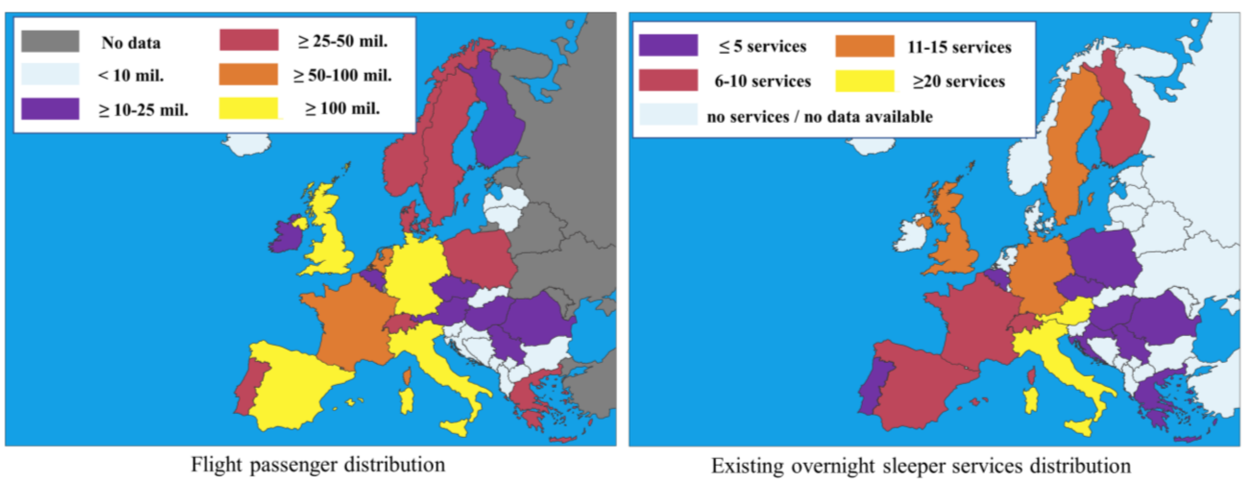


Figure 3-10 Map of Europe's intra-Europe air passenger volume distribution by country versus map of Europe's overnight sleeper services distribution by country. It should be noted that legends have different meanings in two maps.

To give a more direct impression of overnight sleeper routes' service capability, I present an estimation of annual passenger volume based on several assumptions.

A Nightjet's overnight sleeper coach can maximally fit 60 passengers in a couchette coach, 36 passengers in a single-decker sleeper coach[i], 42 or 34 passengers in a double-decker sleeper coach depending on whether the coach has deluxe compartments, which occupies larger spaces [63]. Hence, a coach's capability can range from 34 passengers to 60 passengers under different configurations. As a coach for an overnight sleeper service has similar length to a standard Intercity train, I assume that the number of coaches in an overnight sleeper service is comparable to standard Intercity trains. Taking an example from Swiss Federal Railways (SBB), IC2000 is the type of train connecting some of the most important national hubs, and it operates typically with either five coaches or ten coaches [64]. Therefore, an overnight sleeper service per night can transport $34 \cdot 5 = 170$ to $60 \cdot 10 = 600$ passengers. With the same assumption that all 138 services, as suggested in Section 2.3, operate as daily services, the total passengers transported by overnight sleeper services is roughly $170 \cdot 138 \cdot 365 = 8{,}562{,}900$ to $600 \cdot 138 \cdot 365 = 30{,}222{,}000$ passengers. Under the most aggressive assumptions that each service has ten couchette coaches fully booked, existing overnight sleeper services can transport 30 million passengers annually within Europe, roughly 4.5% of total passengers transported by air within Europe. However, a range of 8.56 to 30.22 million passengers may still be too high, even on the conservative side, because a press release indicated that a popular Nightjet route served more than 100,000 passengers a year, around 140 passengers per day per service [65]. A realistic assumption for passengers carried per day per service should be set below 140 passengers. As a route with over 100,000 passengers has been categorized as high-volume, I take a further discount that 100 passengers per day per service is assumed as the actual average capacity. With such an assumption, total passengers traveled by overnight sleeper services will be reduced to $100 \cdot 138 \cdot 365 = 5{,}037{,}000$ passengers.

An ÖBB's news release about future Nightjet service discloses that the new Nightjet will have seven carriages consisting of two seating carriages, three couchette carriages, and two sleeper carriages [66]. Nevertheless, the current disclosure has no information on each coach's configurations. By applying the assumptions that a couchette or seating carriage can accommodate 60 passengers and a sleeper carriage can accommodate 34 to 42 passengers, a future Nightjet is likely to accommodate 368 to 384 passengers per service. As future Nightjet service's passenger capacity is roughly equivalent to item no.4 in Table 3-1, future Nightjet's passenger capacity information will not be used in further analysis.

Item no.	Assumptions	Max. passenger capacity	Total passenger transported
1	Reduced realistic	100	5,037,000
2	Optimistic realistic	140	7,051,800
3	5 coaches per service - all deluxe sleepers	170	8,562,900
4	Average of Item 3 and Item 5	335	19,392,450
5	10 coaches per service – all couchette	600	30,222,000

Table 3-1 The number of passengers served by overnight sleeper services annually under different assumptions.

With the estimation of annual passenger volume described above, it is relatively straightforward that existing overnight sleepers are mostly serving in Western Europe with a limited number of services that only account for maximally 4.5% of all flight passenger transport volumes.

[i] If a passenger purchase the fare as a private compartment, the entire compartment will be occupied with only one person instead of the maximum capacity of the compartment, reducing the passenger capacity of the overnight sleeper service even further.

Chapter 4 Potential overnight sleeper routes and their deployment strategies

In this chapter, the potential overnight sleeper routes are drawn based on my observations in existing overnight sleeper services and flight routes. The results will be presented in Section 4.1. Section 4.2 will introduce an overlap analysis to check whether existing overnight services have already served a large proportion of proposed new routes. Later, Section 4.3 will demonstrate the carbon saving potentials under different deployment scenarios. In Section 4.4, a detailed analysis of the percentage of passengers that can be transferred to overnight sleepers will be presented with a case study from China's Beijing-Shanghai overnight sleeper services. When Section 4.1 to Section 4.4 discuss mainly on high-volume routes, Section 4.5 provides a brief analysis on the upper limit of overnight sleeper's passenger base to demonstrate the highest amount of flight passengers that can be served with overnight sleepers. In Section 4.6, relevant content concerning potential overnight sleeper routes' deployment strategies in Western Europe and Eastern Europe will be discussed. The last section assessing on overnight sleeper's current potential will conclude this chapter.

Section 4.1 Map of potential overnight sleeper routes

In Section 3.3, I have concluded that the passenger volume in overnight sleeper services is still low. To suggest possible routes for new overnight sleeper services, I propose to start with flight routes with high passenger volumes giving higher chances for new overnight sleeper services to survive. Therefore, potential overnight sleeper routes are based on the flight routes with exceptionally high passenger volumes in 2019, as shown in Figure 3-1.

For flight routes with more than 600,000 passengers in 2019, I have derived their correlated traveling distances and travel times by rail, as described in Section 2.4.

The result in Section 3.3 has suggested that most overnight sleeper services have travel times between 7 and 13 hours. To start with, I use this range of travel times to show the potential routes for overnight sleeper services.

Figure 4-1 shows that 64 flight routes are picked as suitable candidates for deploying overnight sleeper services within reasonable travel times, indicating that in all intra-Europe and domestic routes exceeding 600,000 passengers in 2019, nearly a quarter of them are considered as suitable candidates for deploying overnight sleepers. The filtered 64 routes represented over 83 million passengers in 2019. Such a high volume of passengers per route is a good basis for potential overnight sleeper services as these proposed overnight sleeper routes can have big enough markets to compete with air transport in short haul passenger transport.

Among the 64 candidate routes, 34 are international routes. Germany, Spain, France, the United Kingdom, and Italy have more than three domestic routes discovered. It is noticeable that neither domestic nor international routes involving Eastern Europe are filtered as possible overnight sleeper routes.

The list of filtered routes is presented in Appendix – Tables as Appendix Table 3.

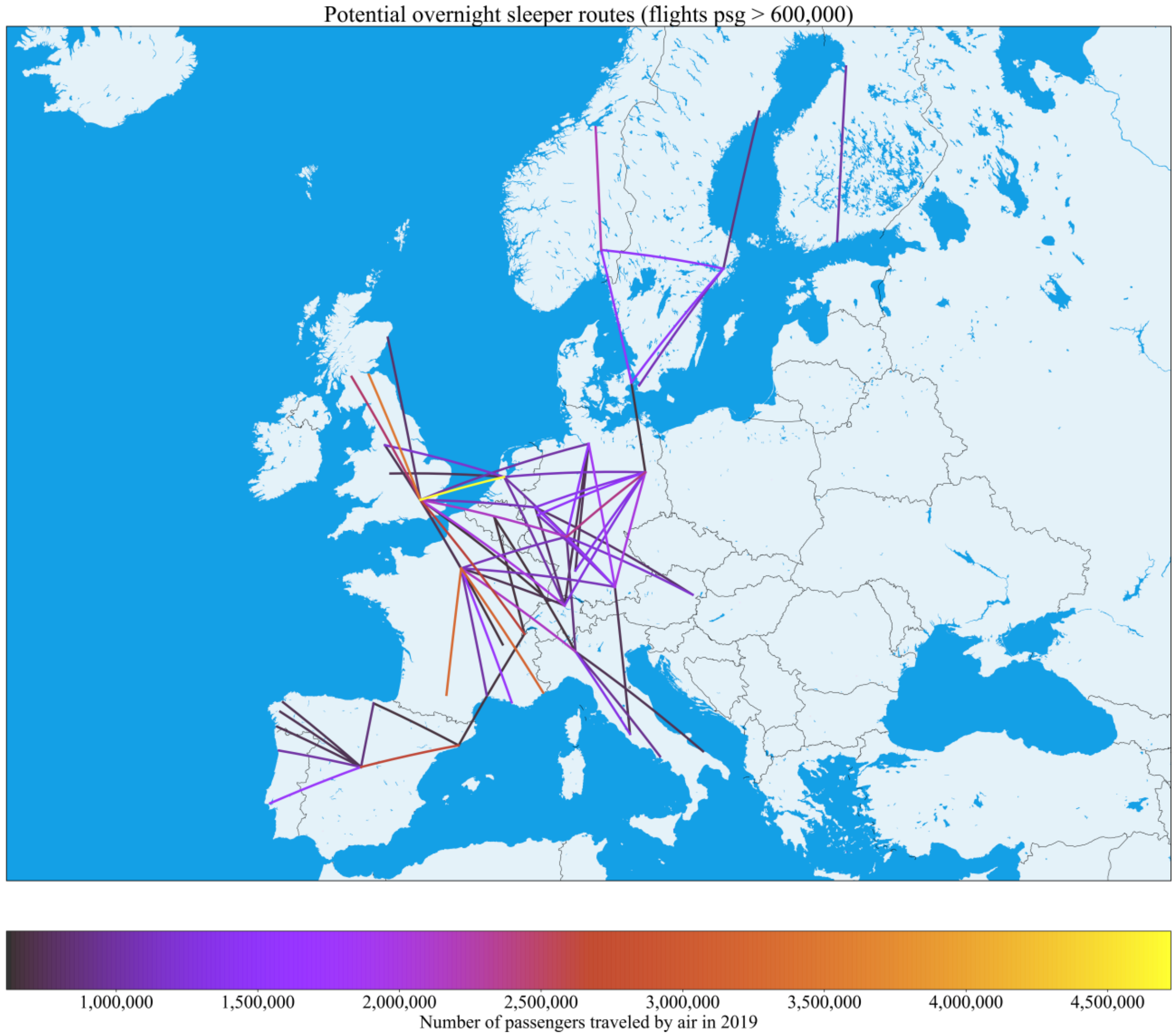


Figure 4-1 Overnight sleeper's potential routes (>600,000 flight passengers in 2019) within 7 to 13 hours of travel times.

Comparing the railway travel distance to the great circle distance, I have summarized that railway travel distance takes 1.42 times longer than the great circle distance among all busy flight routes.

It should be noted that if the range of travel times is set between 7 and 14 hours, 12 additional routes are identified. On the other hand, only a few operating overnight sleeper services have travel times over 13 hours, probably indicating a huge decaying in passengers' attractivity when the travel time is over 13 hours. Therefore, this study will primarily discuss travel times between 7 and 13 hours. In Appendix – Figures, maps of both potential routes between 7 and 14 hours and routes between 7 and 15 hours are presented for reference.

Subsec. 4.1.1 Sensitivity analysis on filtered routes

The sensitivity analysis mainly focuses on the travel speeds of hypothetical overnight sleeper services as travel speeds can directly impact the travel times, leading to the change of replaceability ratio. I have estimated the travel speeds of proposed overnight sleeper services based on existing overnight sleeper services, as described in Section 2.4.

Since the number of available overnight sleeper services is limited in Europe, such a method may deviate from the actual operation speeds. Given derived travel speeds, I present a sensitivity analysis in this subsection. By decreasing or increasing the derived travel speeds, this analysis checks the number of filtered routes on each scenario. Table 4-1 shows that if the derived speeds are decreased by 20%, the routes will be reduced to 53 routes. Further decrease is likely to eliminate suitable routes operating overnight sleepers dramatically. However, when the average speeds are increased, no significant changes on the number of filtered routes can be observed.

Δ in travel speed	Average travel speed (km/h)	Filtered routes	% of total high-volume flights
-60%	33	4	1.7%
-40%	47	28	11.7%
-20%	62	53	22.2%
0%	77	64	26.7%
20%	92	72	30.1%
40%	107	64	26.8%
60%	123	60	25.1%

Table 4-1 Sensitivity analysis on travel speeds' effect on the number of filtered routes that have railway travel times between 7 and 13 hours.

It is arguable that if the travel speed of individual overnight sleeper service can be adjusted to accommodate human beings' biological clock, several more routes can be fitted with overnight sleepers. Nevertheless, different operating speeds on mainlines will impose high pressures on the schedule arrangement for railway operators.

After this sensitivity analysis, I conclude that the current method of estimating travel speeds can capture around 25% of high-volume flight routes and adjusting the travel speeds proportionally from -20% to 60% can capture 25% to 30% of all high-volume flights, indicating that increased train speed does not increase the number of potential routes and that estimated travel speeds can represent a proper ratio of overnight sleeper's replaceability. Maps of selected routes based on different travel speed scenarios are presented in Appendix – Figures from Appendix Figure 12 to Appendix Figure 17.

Section 4.2 Overlap map of potential and existing overnight sleeper routes

In this section, I present an overlap analysis of possible overnight sleeper services and existing overnight sleeper services because Figure 4-1 does not exclude existing overnight sleeper services.

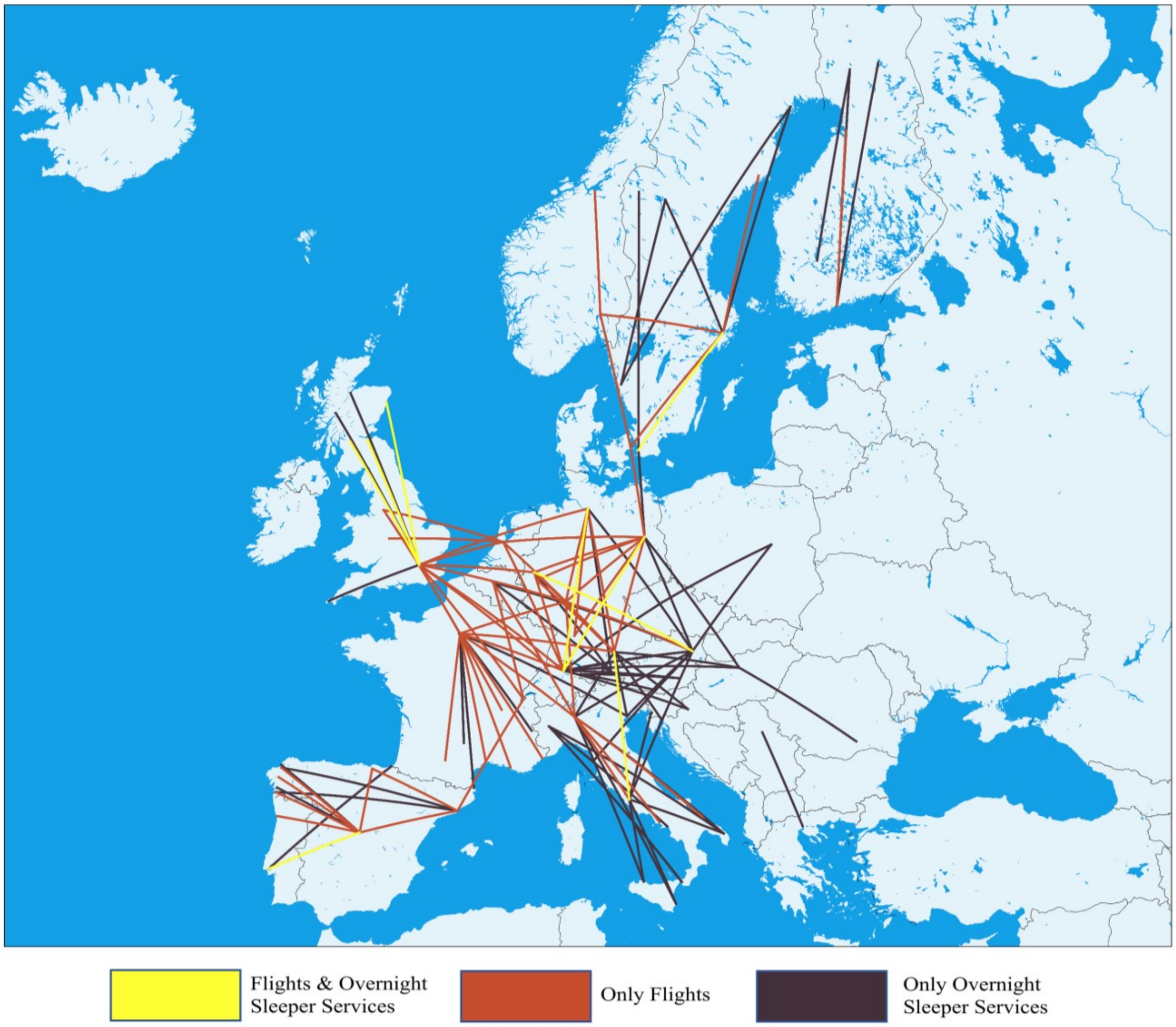


Figure 4-2 Overlap map of possible overnight sleeper services with existing overnight sleeper services. Different colors indicate the operating status.

Figure 4-2 shows that nine flight routes already have pairing overnight sleeper services among 64 routes that are considered potential overnight sleeper routes. Hence, only 14% of proposed overnight sleeper routes are compensated with overnight sleeper services, indicating a business potential for overnight sleeper services, mainly in Western Europe.

Conversely, when I disregard of passenger volumes, I find that 40 out of 69 existing overnight sleeper routes have their pairing flight routes, as shown in Figure 4-3. 24 out of 40 matched existing overnight sleeper services compete on routes with flight passenger volumes below 300,000, leading to the conclusion that a part of existing sleeper routes does not directly compete against flights with the highest passenger flows.

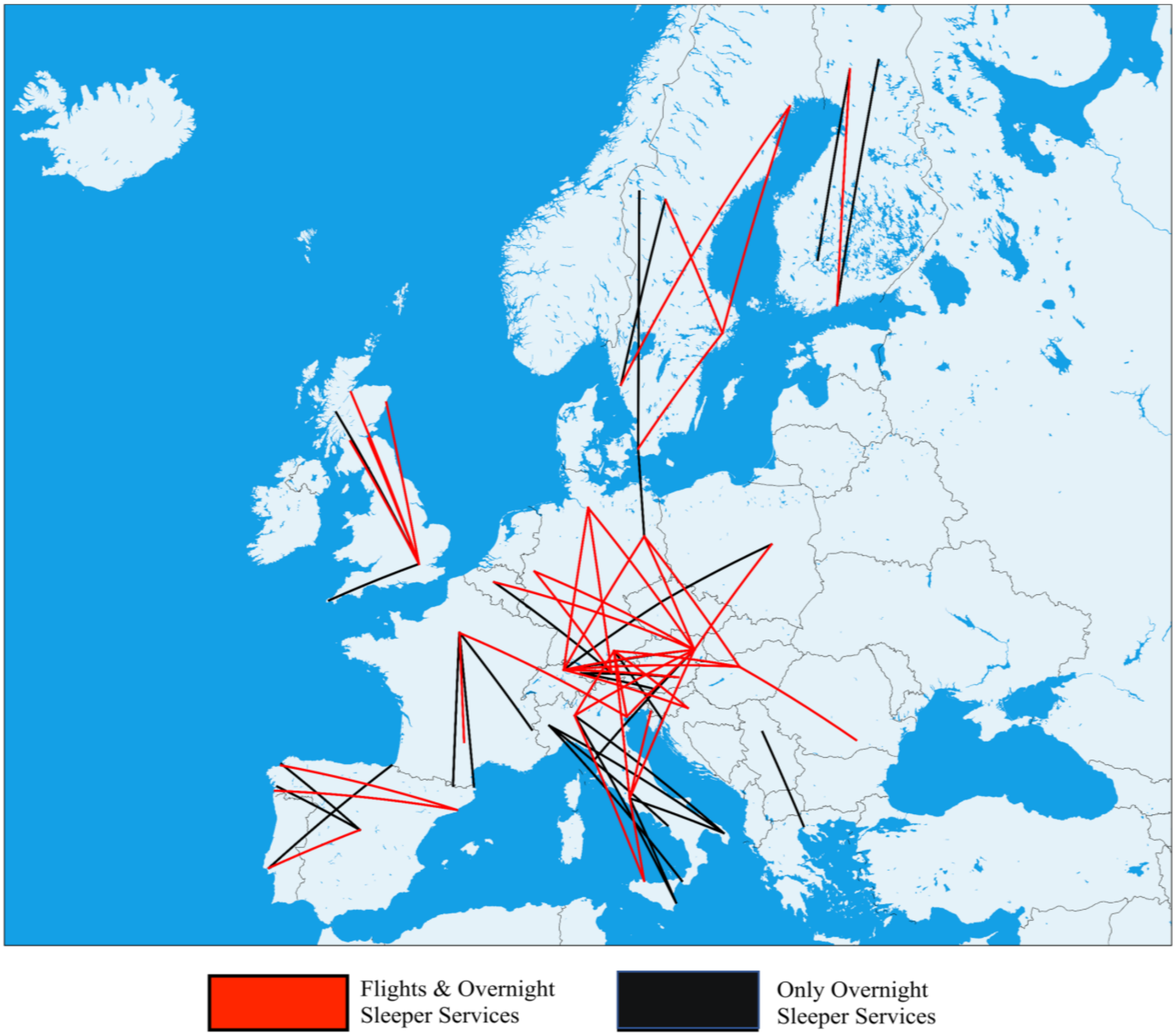


Figure 4-3 Map of existing overnight sleeper routes with red color indicates the route also has flight service while black indicates only overnight sleeper service is available.

Subsec. 4.2.1 Possible business models of existing overnight sleepers

Figure 4-2 has shown that only nine overlaps between the potential 64 routes and existing 69 overnight sleeper routes. Also, Figure 4-3 has shown that many existing overnight sleeper routes do not run in routes where flight passenger volumes are high. Hence, I have derived two types of business models that co-exist for operating overnight sleeper services:

- The overnight sleeper services run on corridors with huge passenger volumes. Instances can be found in London-Glasgow, London-Edinburgh, and Zurich-Hamburg. For these routes, passenger volume is large enough that only a small portion of travelers opting for overnight sleeper services will sustain the business. The discussion of overnight sleeper potential is mainly based on this type of business model.
- The overnight sleeper services run on selected niche routes due to various reasons. In these niche routes, existing overnight sleeper services do not directly compete with the flight services because

airliners may find these routes having less passenger traffic to sustain high-frequency or high-volume services. Instances can be found in Munich/Zurich-Zagreb and Madrid-Ferrol. This proposed business model will not be discussed further due to the lack of information on the overnight sleeper deployment strategies of existing overnight sleeper services.

Provided that two types of business models exist in current overnight sleeper services and that only a small portion of overnight sleeper services directly compete with high passenger volume flight routes, I conclude that most flight routes with high passenger volumes and suitable distances to travel by overnight sleeper services have the business potential to deploy overnight sleeper services to shunt a part of passengers from flights regardless of overnight sleeper's environmental advantages, given that no or little investments on infrastructure will be needed.

Section 4.3 CO_2 reduction by deploying overnight sleeper services

As discussed in Chapter 1, CO_2 emissions per passenger-kilometer for railway and air transport are different. In this section, I present the related CO_2 reduction potential after deployments of the newly proposed overnight sleeper routes under different scenarios. Scenarios range from the basic scenario where I follow the current convention that each day only one overnight service departs per route to the extreme assumption that all passengers will be transferred to overnight sleeper services. All the scenarios will be primarily discussed based on the routes presented in Figure 4-1.

The logic of estimating CO_2 reduction potential is shown in Figure 4-4.

Figure 4-4 Estimation method for CO_2 reduction potential after the deployment of overnight sleepers.

It should be noted that the CO_2 reduction potential is based on operating emissions. Embodied emissions, including potential emissions from infrastructure constructions and other activities, are not discussed.

Subsec. 4.3.1 Basic scenarios and extreme scenarios

In this subsection, I discuss basic scenarios and extreme scenarios. Basic scenarios assume each potential route will deploy one service per direction per day, and extreme scenarios assume all flight passengers in potential routes will be switched to overnight sleepers.

The basic scenario starts with several key variables, which include assumptions. Key variables, shown in Table 4-2, include the number of passengers per overnight sleeper service, the number of services per night for each potential routes, and CO_2 emissions in gram per passenger-kilometer for air and overnight railway, retrieved from the average values of Table 1-1 and Table 1-2. As the number of passengers per overnight sleeper service is not transparent to the public, I use the estimations that I made in Section 3.3.

Scenario	Number of psg. per overnight sleeper service	Number of services per night	CO_2 g per psg kilometer for air	CO_2 g per psg kilometer for overnight sleeper service
100-1 service	100	1	149.6	27.7
140-1 service	140	1	149.6	27.7
170-1 service	170	1	149.6	27.7
385-1 service	385	1	149.6	27.7
600-1 service	600	1	149.6	27.7

Table 4-2 Variables for CO_2 reduction calculation in basic scenarios.

I identify the potential CO_2 that can be saved from the deployment of one daily overnight sleeper service per direction to each route with no overnight sleeper services yet. Therefore, in basic scenarios, for flight routes already having overnight sleeper services, the potential CO_2 reduction is zero as no additional overnight sleeper service is added.

The contributions of possible overnight sleeper services to the total CO_2 reductions under different passenger-carrying capacity are presented in Figure 4-5. Under basic scenarios, considering one overnight sleeper service per day for all potential flight routes, I have estimated that approximately 0.25-1.49 million metric tons of CO_2 will be saved depending on the number of passengers each overnight sleeper service can carry.

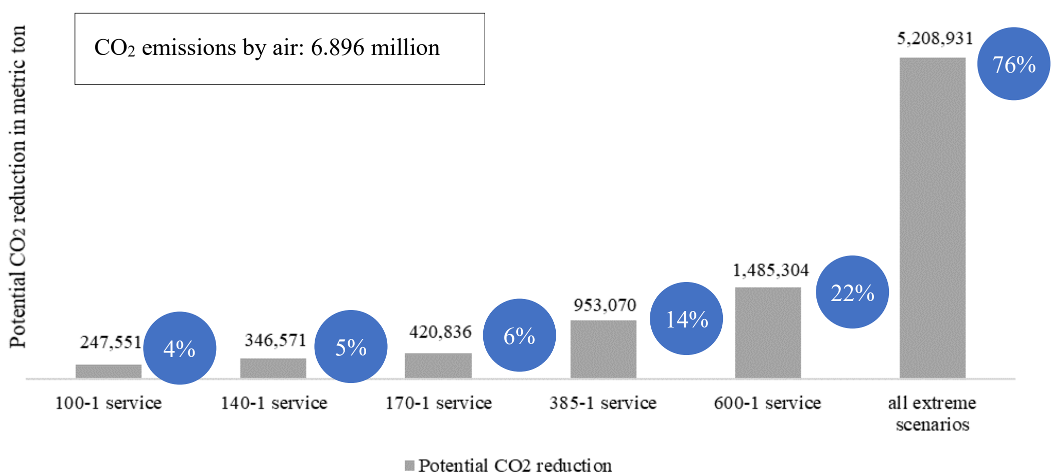


Figure 4-5 Potential CO_2 reduction by deploying overnight sleepers for potential routes under basic and extreme scenarios. The blue circle indicates the CO_2 emissions reduction in percentage compared to original CO_2 emissions all by air.

In extreme scenarios, I assume that all passengers from potential flight routes will be changed to overnight sleeper services disregarding the infrastructure allowances. Assumptions and variables are presented in Table 4-3.

Scenario	Number of psg. per overnight sleeper service	Number of services per night	CO_2 g per psg kilometer for air	CO_2 g per psg kilometer for overnight sleeper service
Xtrm– 100	100	Total psg / 100 / 365	149.6	27.7
Xtrm– 140	140	Total psg / 140 / 365	149.6	27.7
Xtrm– 170	170	Total psg / 170 / 365	149.6	27.7
Xtrm– 385	385	Total psg / 385 / 365	149.6	27.7
Xtrm– 600	600	Total psg / 600 / 365	149.6	27.7

Table 4-3 Variables for CO_2 reduction calculation in extreme scenarios.

As I disregard the constraints in infrastructure, under extreme scenarios, the variable of the passenger-carrying capacity of a single overnight sleeper service plays no role in determining the absolute amount of potential CO_2 reductions, which stays unchanged under five passenger-carrying capacities for potential routes. Under extreme scenarios, converting all passengers from flights to overnight sleeper services will lead to 1.687 million metric tons of total CO_2 emissions, reducing from 6.896 million metric tons, accounting for only 24.5% of CO_2 emissions by flights, and indicating a 75.5% CO_2 savings, as shown in Figure 4-5.

Subsec. 4.3.2 In-between scenarios

In the previous two subsections, I have discussed the basic scenarios where I expect all potential routes will have one overnight sleeper service per day per direction and the extreme scenarios where overnight sleeper services will replace all passengers from potential flight routes. Possible CO_2 reduction ranges from 4% to 75.5% based on estimations under basic and extreme scenarios.

From Figure 4-5, it is clear to say that the CO_2 reduction potential is very sensitive to the number of passengers per potential overnight sleeper service can carry. In this subsection, the discussion will mainly focus on the number of passengers that potential overnight sleeper services can carry in total per year instead of the number of services per day by assuming the passenger-carrying capacity of the service for each of the routes. The number of services per day can be deduced under different assumptions on passenger-carrying capacities.

Figure 4-6 presents the potential CO_2 reductions under different passenger splits by flights and overnight sleeper services. The potential CO_2 reduction reduces linearly as the percentage of passengers carried by flights increases.

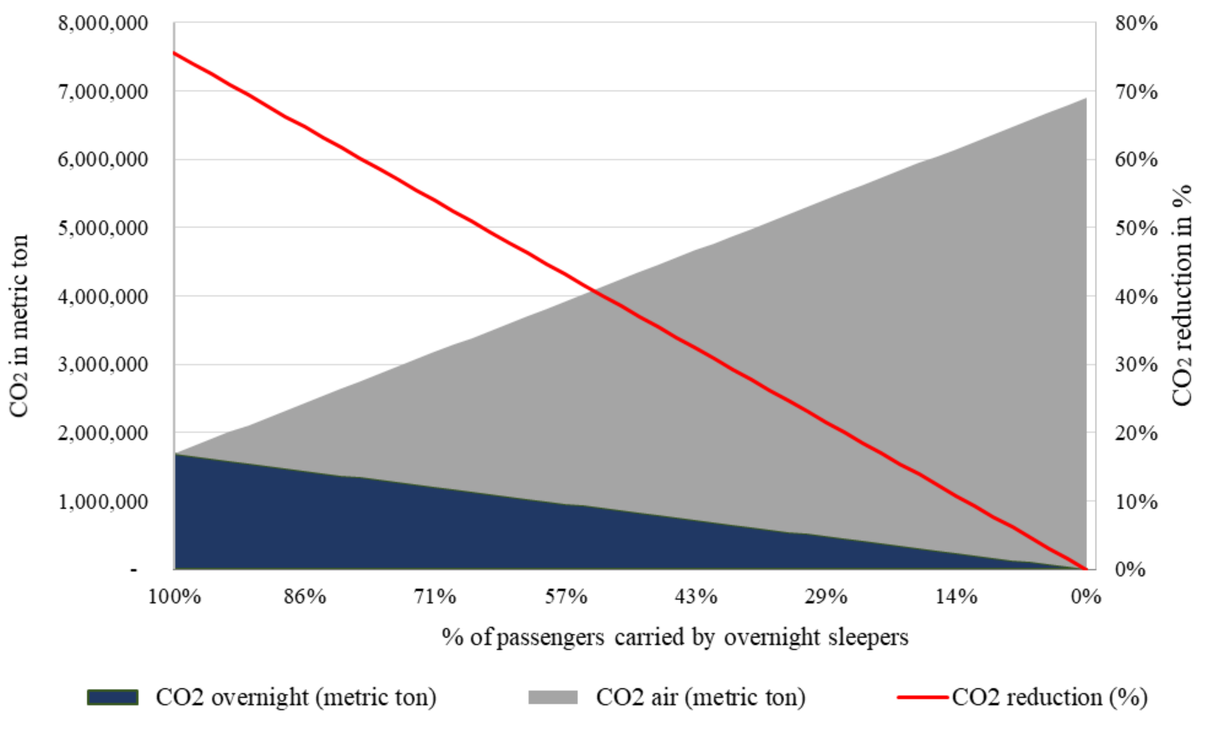


Figure 4-6 CO_2 reductions under different percentages of passengers carried by overnight sleepers. Right axis indicates the percentage of CO_2 reduction.

Figure 4-7 illustrates the number of passengers that overnight sleeper services and flights need to take annually under different scenarios. Under the most extreme cases, over 83 million flight passengers from 64 potential routes need to be transported by overnight sleeper services. Depending on each train's passenger capacity, around 400 to 2200 trains will be needed per day to fulfill the annual demand of 83 million passengers.

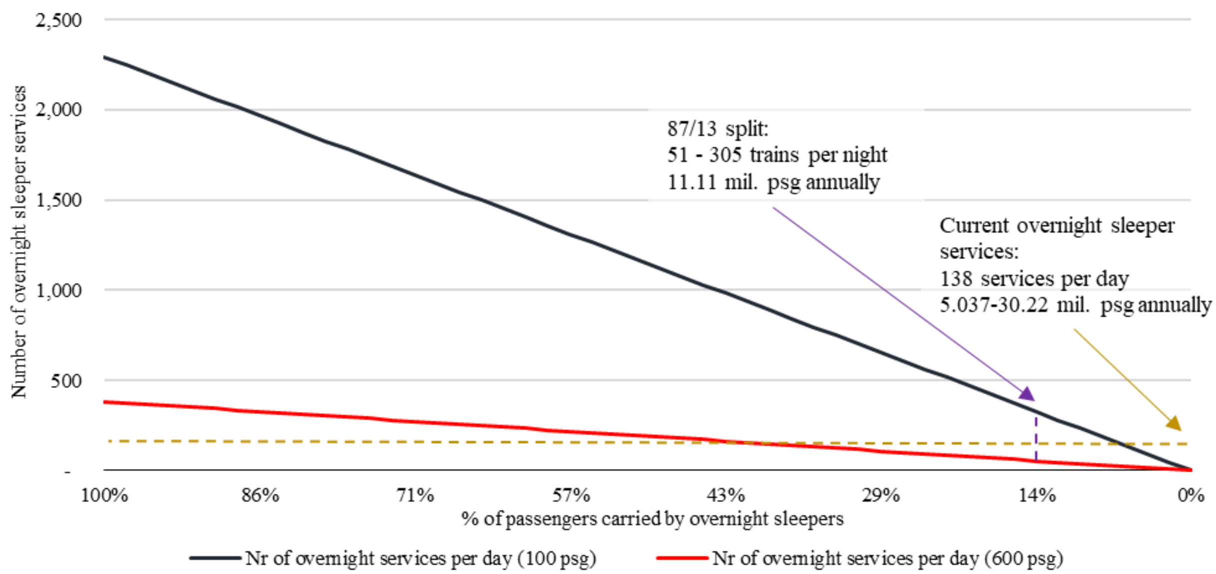


Figure 4-7 Number of overnight sleeper services needed each day when passenger capacities are 100 and 600 per service, respectively. Purple dashed line indicates the number of services needed to carry 11.11 million potential passengers under 87/13 split. Brown dashed line indicates the number of existing overnight sleeper services, serving 5.037 to 30.22 million passengers.

Section 4.4 The equilibrium between air and overnight railway

As discussed in Section 4.3, replacing some flights with overnight sleepers affects the reduction of CO_2 emissions in operations. This section's discussion is more on how to find a balance between overnight sleeper and flight services.

Potential CO_2 reductions under different scenarios are presented in Section 4.3. Nevertheless, I did not consider the constraints of infrastructure and personnel, including but not excluding the availability of railways, the availability of railway platforms/tracks for all involved stations, and the availability of train crew and traffic controllers. To understand the balance point where no massive investment in infrastructure and workforces in both the railway and air sectors is needed, this section's discussion proposes a reasonable split of overnight sleeper services and flight services. As overnight sleeper service is an emerging or re-emerging business in Europe, the current passenger split of air versus overnight railway for each existing overnight sleeper route depends almost solely on the total number of flight passengers, leading to biased results; therefore, a case study on a mature business case for its passenger split between air and overnight railway can provide guidance.

As a result of this, I present an operating business case of Beijing-Shanghai overnight sleeper services to view how an established overnight sleeper service competes and lives along with a high passenger volume flight route.

Case study of Beijing-Shanghai overnight high-speed sleeper services

An example of existing overnight sleeper services outside Europe with stable passenger volume is Beijing's overnight sleeper service to Shanghai. The same corridor had a flight passenger volume of 6,518,997 in 2018 [67].
Three daily high-speed railway overnight sleeper services and one normal speed express overnight sleeper operate in each direction, as shown in Table 4-4. As Beijing-Shanghai high-speed railway was constructed primarily for daytime operations, and the platform availabilities at night are generally high in involved stations, I consider the overnight sleeper services in the Beijing-Shanghai corridor as a case leveraging existing infrastructure.

	Z282	D702	D706	D710
Shanghai Station depart:	-	19:09	21:18	21:24
Shanghai South station depart:	19:30	|	|	|
Beijing South station arrive:	|	|	|	09:22
Beijing Station arrive:	10:22	7:12	9:24	-

Table 4-4 Schedule of available overnight sleeper services from Shanghai to Beijing. The table is modified from [68].

The high-speed sleeper trains operating in the Beijing-Shanghai corridor has a passenger capacity of 40 passengers per coach. One service typically has eight coaches, giving a total passenger capacity of 320 passengers. Therefore, I can conclude that there are around 2560 passengers who travel by overnight sleepers in the Beijing-Shanghai corridor per day in both directions. Annually, based on such an estimation, nearly one million passengers traveled by high-speed overnight sleeper services in the Beijing-Shanghai corridor.
Combining the number of passengers by flights amounting to 6.5 million as of 2018 with the number of passengers by high-speed overnight sleeper services, at least 7.5 million passengers traveled in the Beijing-Shanghai corridor per year. Under the assumption that overnight sleeper services and flights are the only two complimentary public transportation modes in the Beijing-Shanghai corridor, it can be derived that the split of the total number of passengers between the two modes is 13:87.
However, this estimation method also has its limitations. To estimate the total number of passengers traveling in the Beijing-Shanghai route, I should also include the number of passengers traveling by daytime high-speed railways. In 2019, nearly 54 million passengers traveled in the Beijing-Shanghai corridor by daytime high-speed railways through 36 services per direction per day, and each passenger traveled 638 kilometers on average [69]. Nevertheless, the number of passengers who traveled the entire Beijing-Shanghai corridor is not publicly available, leaving the passenger flow of Beijing-Shanghai daytime high-speed services hard to estimate.
Regarding the ratio of overnight sleeper services per night to the availability of tracks in relevant stations, Beijing-Shanghai's business case can also provide a benchmark. In Beijing, on certain days in a week, 20 high-speed overnight sleeper services depart for various destinations with its two main stations, Beijing West and Beijing South. Both stations have more than 20 tracks. In Shanghai, 25 high-speed overnight sleeper services depart from Shanghai Hongqiao and Shanghai Station on certain days in a week. Shanghai Hongqiao and Shanghai Station have more than 40 tracks combined [70]. A brief conclusion for benchmarking is that the ratio between the number of overnight sleeper services to the number of tracks available in the stations ranges from 50% to 62.5% at two of China's largest cities.

From the Beijing-Shanghai case study, I have estimated that when every 87 passengers travel by air, 13 passengers will travel by overnight sleeper services. Using 87/13 split as a benchmark to apply numbers of passengers for potential European overnight sleeper routes, I can narrow down the number of overnight sleeper trains that need to be deployed. Under different passenger-carrying capacities, 51 to 305 trains will be required each day to meet the additional travel demands of 11.11 million passengers, as shown in Figure 4-7. Such a split will save 711989 tons of CO_2. 711989 tons of CO_2 is relatively a limited figure compared to 1097 million tons of CO_2-equivalent emissions from all transport means within the E.U. [71].

The Beijing-Shanghai case also provides a benchmark on relating the number of overnight sleeper services a city can carry to the scale of the railway station infrastructure. To break down the additional overnight sleeper services into each route, I estimate the additional number of services needed for each route to see the potential cities with high stress in serving additional overnight sleeper services.

By assigning the number of passengers from flights to overnight sleeper services with an 87/13 splitting rule for all potential routes, I have estimated the number of additional overnight sleeper services for each city based on the equal split of the number of passengers going inbound and outbound. Table 4-5 shows that 13 cities will be required to serve at least 10 more overnight sleeper services per day if one service has 100 passenger-carrying capacity. It should be noted that the sum of additional trains will be higher than the assumption of our previous statement, in which 51 to 305 overnight sleeper services would be needed, because of the rounding up.

Through the case study of Beijing-Shanghai, I have estimated that the ratio of the number of overnight sleeper services of a city to the total available tracks in a city's stations can be up to 62.5%. I define this ratio as the tracks' utilization rate for overnight sleeper services under the current context. As shown in Table 4-5, London, Paris, and Berlin will face high stresses for the addition of overnight sleeper services. If Beijing or Shanghai's utilization rate of tracks can be achieved, London, Paris, and Berlin will require 79, 47, and 40 tracks, respectively.

City	Sum of additional trains @ 100 psg capacity per night	Sum of additional trains @ 600 psg capacity per night	Required number of tracks @ 62.5% utilization rate @ 100 psg capacity	Required number of tracks @ 62.5% utilization rate @ 600 psg capacity
London	44	13	71	21
Paris	29	9	47	15
Berlin	25	8	40	13
München	19	7	31	12
Amsterdam	19	7	31	12
Frankfurt	18	6	29	10
Madrid	18	7	29	12
Milano	15	6	24	10
Zurich	15	6	24	10
Hamburg	13	5	21	8
Duesseldorf	12	5	20	8
Stockholm	10	4	16	7
Oslo	10	3	16	5

Table 4-5 Cities with high service pressure to meet 87/13 split between air and overnight railway passengers and estimated numbers of tracks in stations needed.

It should be noted that the required number of tracks for each city in Table 4-5 is only a proxy to assess the potential stress from the deployment of overnight sleeper services. The required number of tracks refers to all available tracks that can serve overnight sleeper departures within and around the city. For all cities displayed in Table 4-5, I have identified two types of scenarios. Corresponding suggestions are given as below:

- London, Paris, Madrid, Milan, and Hamburg are cities with multiple terminal railway stations [72-78]. London and Paris have more than 50 tracks that have the capability of serving long-haul departures. For Madrid, Milan, and Hamburg, each city has two terminal stations that have at least 30 tracks in total. Based on the case study of Beijing-Shanghai, this study proposes that cities with two or more terminal stations can leverage each station's geographical advantages and serve overnight sleeper services based on traveling directions.

- The rest of cities in the table have one terminal station that has the capability of serving departures of overnight sleeper services. For these cities with limited tracks but rather great potential demand for overnight sleeper services, I propose that cities may integrate infrastructure resources from nearby regions, allocate departures to stations with higher availability, and satisfy the demand by operating stop-overs to stations where large passenger volumes are expected. For instance, in Germany's Ruhr area, six Category-1 stations with strong capabilities of serving overnight trains can be allocated with multiple overnight sleeper services according to each station's availability [79].

Section 4.5 Upper limit of passengers replaced by overnight sleepers

In addition to the analysis of 64 high-volume routes, I present an upper limit estimation on overnight sleepers' passenger volume by considering all flights with suitable distances can be replaced by overnight sleepers.

As stated in Section 4.5, railway travel distance is expected to be 1.42 times longer than the great circle distance, and current overnight sleepers have an average travel speed of 71.86 km per hour. For all flight routes that I obtained from Eurostat, I estimated their railway travel distances and railway travel times by multiplying their great circle distances by 1.42 and dividing 71.86 km per hour. Regardless of geographical constraints, I filtered 339 routes that are considered as suitable routes for operating overnight sleeper routes. 339 routes carried 148.9 million passengers in 2019. Compared to the extreme scenario where I considered only popular 64 routes with more than 83 million passengers, analyzing all flight routes do not significantly increase the number of potential overnight sleeper passengers.

If the geographical constraints are applied, such as overnight sleepers cannot operate between islands, I have summarized that around 70% of filtered routes are available for railway operation, indicating that $148.9 \cdot 70\% = 104.23$ million passengers can be carried by overnight sleepers. A passenger base of 104.23 million can be considered as the upper limit that can be served with normal speed overnight sleepers, and 104.23 million passengers roughly account for 17% of all domestic and intra-Europe flight passengers.

As potential 64 overnight sleeper routes had over 83 million passengers by air in 2019, I consider 104.23 million passengers as a limited passenger base increase. By assuming a passenger split of 87/13, which can already stress some cities' railway infrastructures when only considering 64 high-volume routes, overnight sleepers can displace 13.55 million passengers. In the last section, I have concluded that deploying overnight sleepers in the 64 high-volume routes with an 87/13 air-to-railway passenger split ratio has negligible carbon savings effects. Increasing the passenger base from 11.11 million to 13.55 million passengers by considering all flight routes in Europe is unlikely to improve the carbon reduction effect.

Therefore, I conclude that my previous methods based on passenger volumes already captured a relatively high passenger base for displacing overnight sleeper services. Expanding to all flight routes collected from Eurostat for filtering potential overnight sleeper routes cannot significantly increase the potential market size. Consequentially, the increment of carbon savings by considering a wider range of flights is negligible compared to the total carbon emissions from the transport sector. Such a conclusion also indicates that incentivizing overnight sleepers in the short run for environmental reasons may not be compelling enough.

Section 4.6 The asymmetry between Western Europe and Eastern Europe

When my study mainly focuses on replacing flight routes with adequate distances allowing for overnight railway traveling and large passenger volumes, I observed an asymmetry of potential overnight sleeper routes between Western Europe and Eastern Europe. Flight statistics also show fewer traffic volumes in Eastern Europe, as discussed in Section 3.1. Several possible reasons could explain the asymmetry of potential overnight sleeper routes and high-volume flight routes between Western Europe and Eastern Europe.

It is first worth mentioning that flight routes with high passenger volumes in Eastern Europe often connect to destinations in Western Europe, leading to long distances not favored by overnight sleeper services. This observation has been described in Section 3.1, where I stated that high passenger volume flight routes in Eastern Europe are usually connected to Western European destinations.

The second possible reason is that the gap in railway infrastructure between Western Europe and Eastern Europe is relatively large. The operating and rail systems existing in some Eastern European countries were too old to modernize or upgrade to fit the current infrastructure [80]. Figure 1-5 also shows that Western Europe has a higher share of multi-track mainlines in normal speed railway, while Eastern Europe's mainline consists of more single-tracks. Therefore, in both the operating status of railway infrastructure and platform availability, Eastern Europe shows disadvantages. However, Western Europe has already developed a relatively mature railway network leading to a significant number of experiences and technology reserves. Western Europe's experiences and technologies in railway transport may help a delayed modernization of railway networks in Eastern Europe.

The third possible reason is that Eastern Europe has less capability to serve flights, leaving the number of passengers traveled by air an unfavorable proxy to predict the travel demand. Indicators such as the total fleet size can validate such an argument, as shown in Figure 4-8. This idea can also be tested by introducing another metric defined as the number of intra-Europe and domestic flights per capita taken in a year. In Figure 1-1, I have already presented the passenger volume distributions by countries in the EU28. By adding the population by country data provided by the World Bank, I produce the number of intra-Europe and domestic flights per capita in 2017 [82]. Figure 4-9 shows that several Eastern European countries offer below-average flight trips per capita, partially supporting the conclusion that Eastern European countries have a generally less passenger-carrying capacity in air transport. Therefore, it is less accurate to estimate overnight sleeper services' potential demand using air transport passenger data.

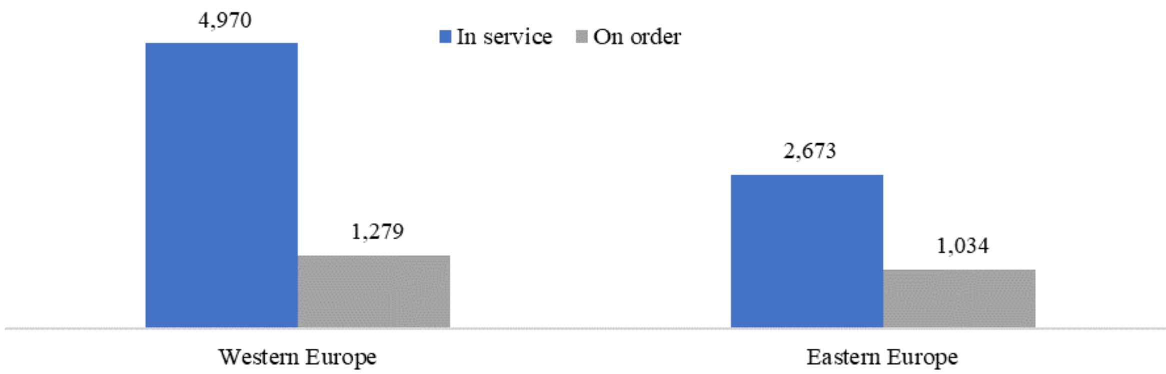


Figure 4-8 Fleet size comparison of passenger airplanes between Western Europe and Eastern Europe[i], modified from [81].

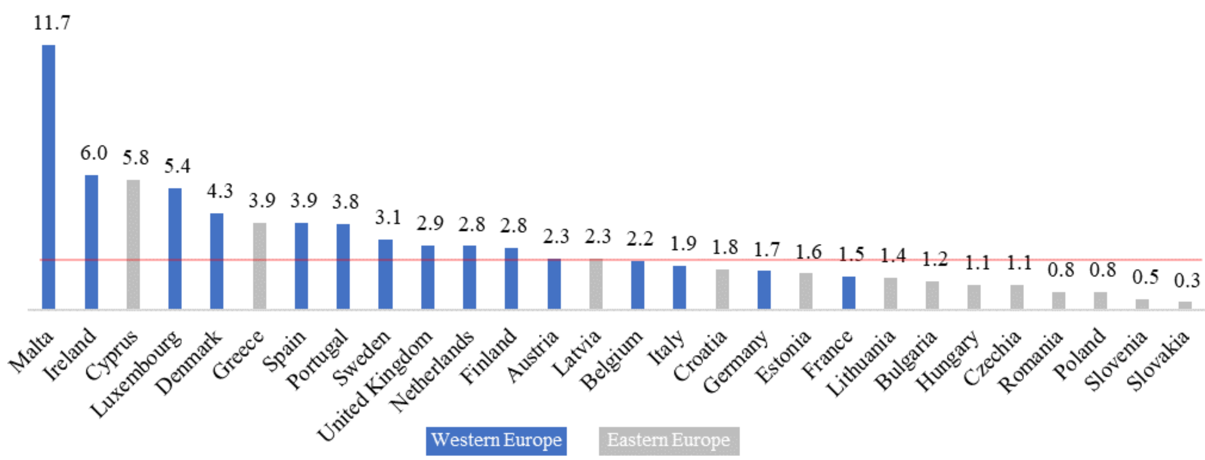
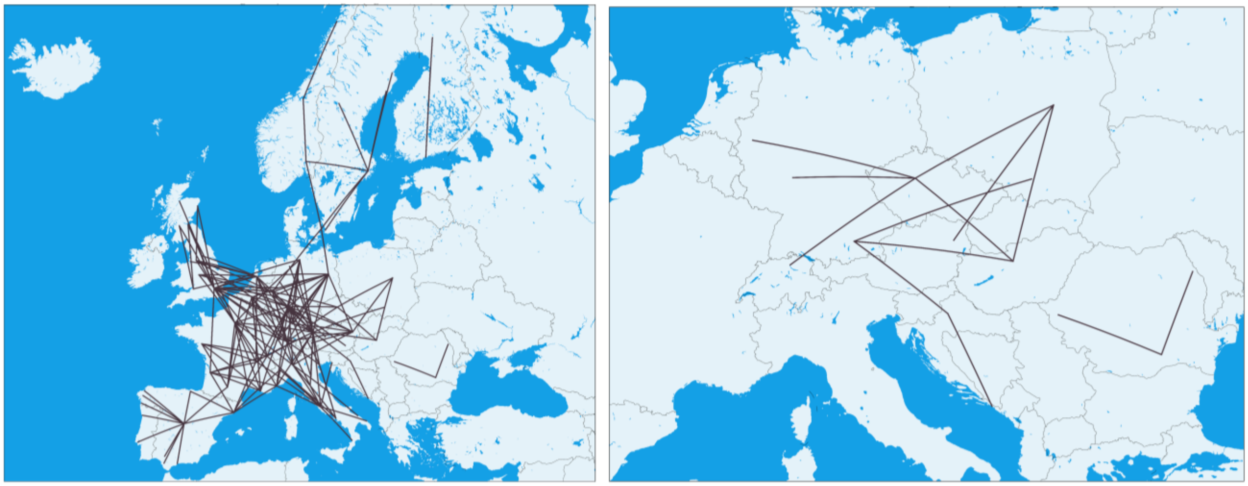


Figure 4-9 The number of intra-Europe and domestic flights per capita taken in 2017 in descending order, derived from [5, 82]. Eastern Europe had 1.74 flights per capita in 2017, while Western Europe had 3.75 in the same period. The red line equals 2.2 intra-Europe and domestic flights per capita, the EU28 average.

The solution to predict Eastern Europe's potential overnight sleeper routes, which are omitted by the high passenger volume required before, is lowering the barrier of passenger volume. Figure 4-10 presents a map produced with the same logic as Figure 4-1 but lowers the passenger volume barrier from 600,000 to 200,000. Although several routes have been filtered out in Eastern Europe, including two domestic routes in Romania, Figure 4-10 shows a similar asymmetry as Figure 4-1.

[i] Western Europe includes Austria, Belgium, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greenland, Guernsey, Iceland, Ireland, Isle Of Man, Italy, Jersey, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom.
Eastern/Central Europe includes Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Georgia, Greece, Hungary, Kosovo, Latvia, Lithuania, Moldova, Montenegro, North Macedonia (FYROM), Poland, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Turkey, Ukraine.



Potential overnight sleeper routes (flights psg > 200,000) | Potential Eastern European overnight sleeper routes (flights psg > 200,000)

Figure 4-10 Map of potential flight routes (>200,000 passengers in 2019) that be reached by overnight sleeper services within 7 to 13 hours with an enlarged map of Eastern European routes (>200,000 passengers in 2019).

The asymmetry of air transport between Eastern Europe and Western Europe results in an asymmetry of potential overnight sleeper services' geographical locations. By applying a different selection criterion, I have sieved several more potential overnight sleeper routes in Eastern Europe while the asymmetry persists. Since a high passenger volume of air transport implies a high potential customer base for overnight sleeper services, I recommend that new overnight sleeper routes should mainly deploy to the routes shown in Figure 4-1.

Subsec. 4.6.1 Different deployment strategies of overnight sleeper services for Eastern Europe and Western Europe

From a business perspective, I suggest applying different deployment strategies to Western Europe and Eastern Europe. Primary deployment of overnight sleeper services should be in Western Europe for its higher customer volumes. In Eastern Europe, it is likely that current passenger volumes, especially in short haul public transport, are not entirely revealed by the number of passengers carried by the available transportation modes.

Region	GDP per capita (2009) in USD	GDP per capita (2019) in USD	GDP per capita growth (2009-2019)	Projected GDP per capita (2050) in USD
Eastern Europe (excl. Greece)	12,499	16,319	2.70%	37,307
Western Europe	40,072	41,316	0.31%	45,421

Table 4-6 Per capita comparisons between Eastern Europe and Western Europe in GDP (2009, 2019, and projected values at 2050 with current growth rates), and GDP growth rate, derived from [5, 82, 84]. The growth rate is calculated as the compound annual growth rate. It should be noted that Greece is excluded as its recent recession occludes the uprising performance of the rest of Eastern European counties.

Other evidence also supports the observation that Eastern Europe has large markets for short haul public transportations, but the supply may not satisfy the demand. It has been estimated that in Eastern Europe, the predicted increase of the total passenger transport demand is 149 %, and the rise in car travel is 96% by 2050 because of the increasing economic growth and increased affordability of private cars [83]. Furthermore, Table 4-6's data substantiates that although Eastern Europe has a lower GDP per capita in both 2009 and 2019, it has been observed with a faster growth rate narrowing its productivity gap with Western Europe. At 2050, it is expected that GDP gap between Western Europe and Eastern Europe will be narrowed down to 8000 USD per capita, indicating a higher likelihood of an integrated Europe.

With the anticipation of economic growth in Eastern Europe, mobility is projected to grow as well. As shown in Figure 4-8, even though the fleet sizes had a massive difference between Western Europe and Eastern Europe, on-order fleet sizes were somewhat alike.

Since the gap in railway infrastructure between Western Europe and Eastern Europe is relatively large, I propose different strategies to deploy overnight sleeper services in Eastern Europe. In Western Europe, potential sleeper routes are considered as a splitter of existing passenger volumes from flights by utilizing existing railway networks. In Eastern Europe, overnight sleeper services are suggested to address passengers who are not served by existing air or railway transports due to the lack of serving capabilities. Admittedly, introducing more railway services will need new investments in Eastern Europe. In the long run, investment in railway infrastructure will keep Eastern Europe with the European Commission's initiatives to integrate the European transport area as one entity [85]. Therefore, improving Eastern Europe's railway infrastructure will be a long-term benefit for Eastern Europe. Potential deployments of overnight sleepers will also benefit from better railway infrastructure.

I close the discussion on Eastern Europe here, and I suggest a further specialized study in Eastern Europe's current railway services capabilities and potential investments needed to guide Eastern Europe's transport sector and further reduce its carbon footprints.

Section 4.7 Assessment on overnight sleeper's current potential

Based on the scenario analysis of carbon savings and reasonable passenger split between overnight sleepers and air transport for potential 64 routes, I have estimated that about 11 million passengers can be transferred from air transport to overnight sleeper services saving around 711 thousand tons of CO_2. In this section, I present a summarized assessment of overnight sleeper's potentials at current stages, from both environmental and business perspectives.

In 2018, 28 member states of the E.U. produced 182.45 million tons CO_2 through air transport, and 711 thousand tons of CO_2 roughly represents a CO_2 reduction of 0.4%[i] [20]. A 0.4% reduction of CO_2 is considered as a negligible impact on reducing carbon emissions by conducting modal shift utilizing existing railway infrastructure. Furthermore, the annual increase of CO_2 in air transport worldwide from 2018 to 2019 was 20 million metric tons, and the E.U., under the same assumption as in Method Description 2 in Appendix – Descriptions of analysis, can be attributed to 17.6%[ii] of the additional CO_2 increment, indicating an annual increase of 3.5 million tons of CO_2 [13-15]. Therefore, a CO_2 saving of 0.711 million tons of CO_2 plays a negligible role in effectively reducing carbon emissions from both the aspect of reducing the total carbon emissions in air transport and the aspect of mitigating the uprising trend of carbon emissions from air transport. It is arguable that an aggressive modal shift strategy that replacing most flights with overnight sleeper services, as discussed in extreme scenarios in Subsec. 4.3.1, can have rather large impacts on carbon reductions. Nonetheless, Section 4.4's passenger split analysis based on a mature business case has shown that the 87/13 passenger split ratio can already stress existing railway networks, and further additions of overnight sleeper services on the filtered 64 routes will inevitably require new investments in

i $\frac{0.711}{182.45}\% = 0.4\%$

ii $\frac{1.181 \text{ billion passengers} \cdot 64\%}{4.3\ billion\ passengers} = 17.6\%$

infrastructure and other supporting fields. Therefore, from carbon saving's perspective, overnight sleepers face the dilemma that existing conditions only allow a limited amount of new overnight sleeper services resulting in negligible carbon savings while significant effects on carbon savings will require additional investments and efforts on deploying overnight sleeper services, possibly leading to path dependency in the future. Therefore, the overnight sleeper is hardly an option to effectively reduce carbon emissions in the short run.

From the viewpoint of business potential, the proposed 64 routes had an average air traffic volume of over one million passengers, providing a good customer basis for deploying new services. Furthermore, most routes involve cities that were identified as hotspots in Section 3.2. Hotspots and their airports have a higher share of aircraft movements, indicating saturated utilization rates. Moreover, airport expansion programs are difficult to realize, especially in densely populated areas where air traffic is also expected to be dense [86]. Therefore, overnight sleeper services have the potential to relieve traffic pressures in busy airports.

In the short run, deploying overnight sleepers has a negligible influence on carbon savings but has a business potential on selected routes depressurizing saturated airports. As high-speed railway and normal daytime railway have their constraints in displacing air transport, as discussed in Chapter 1, I conclude in this chapter that in the short term, overnight sleeper service is a business opportunity for railway operators to exploit new growth in routes with high flight passenger volumes. However, at the current stage, it is likely that railway transport, including overnight sleepers, cannot provide environmental incentives to effectively decarbonize short-haul passenger transport.

Chapter 5 Winners for short-haul passenger transport in the long run

In the previous chapter, I have studied the potential of overnight sleepers and concluded that overnight sleepers have limited impacts on decarbonization efforts in short-haul passenger transport at the current stage. However, short-haul passenger transport must be reformed to drastically lower carbon emissions in the long run. In this chapter, I will discuss how passenger demands can be satisfied in the long run, based on feasible transport modes. Specifically, the chances of overnight sleepers and general railway transport, in the long run, will be discussed with the potentials of synthetic air fuels under the challenging decarbonization targets. The comparison will be presented in Section 5.1. In Section 5.2, based on railway transport's competitive advantages, I will discuss further possible improvements to railway transport. This chapter is also closed by a summary.

Section 5.1 Air transport with synthetic fuels versus railway transport

I compare two transport modes in this section, air transport under synthetic fuel scheme and railway transport, with two metrics: specific energy consumptions and environmental impacts. The comparison is set in the long run, assuming that the electricity supply to the transport sector will be carbon-free.

Air transport is widely seen as the most challenging transport mode to decarbonize because of its long lifecycles of existing infrastructure and aircraft and its engine technologies leading to limited alternative fuel options [87, 88]. For instance, despite hydrogen fuel being publicized as the most environmentally benign alternative to petroleum, its lightweight, production, handling, infrastructure, and storage offer significant challenges. Options to reduce air transport emissions have been narrowed to a small range of alternative fuels. Two of the most promising alternative fuels are biofuels and carbon-neutral synthetic fuels. The latter one is suggested to be prioritized as financing biofuels will have higher costs in the long run [89].

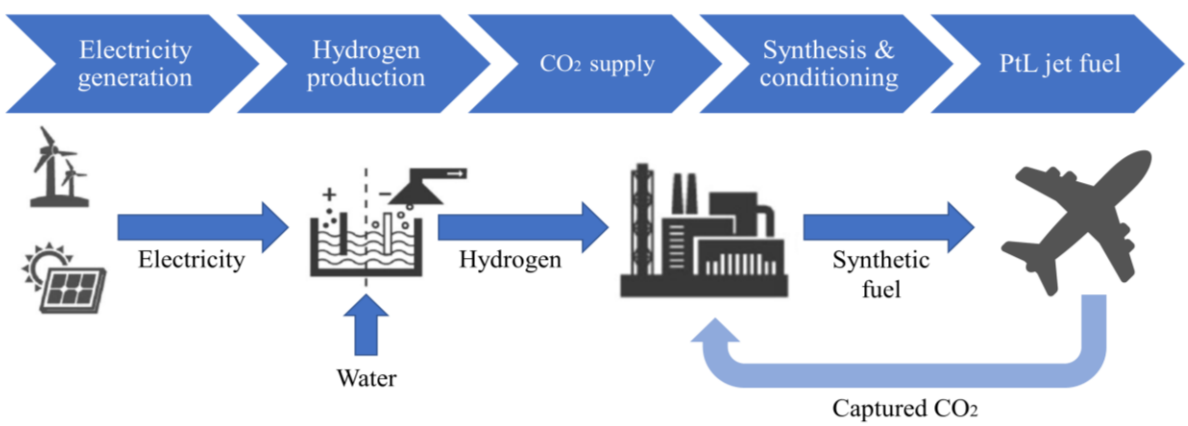


Figure 5-1 Generic production process of synthetic fuels by power-to-liquid process, modified from [90, 91].

Although synthetic fuel is of financial advantage to biofuels and can achieve very high carbon emissions savings, it has more complicated production processes than conventional aviation fuels. The production process of synthetic fuel based on the power-to-liquid method is presented in Figure 5-1. Complicated production processes lead to high production costs. Studies indicate that the production cost will be around 1352 euros per ton in 2050 with the production ramp-up and favorable electricity prices [16, 88, 90, 92, 93].

Specific energy consumptions

This part's discussion between synthetic fuel and railway transport will compare both modes' specific energy consumptions. Specific energy consumption is defined as energy consumption for transporting a passenger one kilometer. Table 5-1 shows that both air transport and railway have increased their energy efficiencies from 1990 to 2018 and that air transport produces significantly higher carbon emissions than railway transport.

Transport mode	Energy consumption (kWh per passenger-kilometer)
Air (1990)	1.22-2.03
Medium-long distance railway (1990)	0.23-0.28
Air (2018)	0.28-0.86 (mean = 0.5)
Railway (2018)	0.03-0.22 (mean = 0.06)

Table 5-1 Energy consumption per passenger-kilometer by air and railway transports with passenger occupancy rates already applied [94-96]. Energy consumption includes the primary energy consumption and energy used in fuel production and electricity distribution (i.e., well-to-wheel).

Under the synthetic fuel scheme, the production efficiency of synthetic fuels needs to be considered as well. synthetic fuel has two production pathways, methanol pathway and Fischer-Tropsch pathway. Both pathways have two types of CO_2 input types, direct air capture and concentrated input, and both pathways have a production efficiency of 39% under direct air capture of CO_2 and that of 47% under concentrated CO_2 input [90]. Therefore, to fairly compare the energy consumption per passenger-kilometer, I have applied the efficiency difference between producing synthetic fuel and producing conventional aviation fuel. Conventional jet fuel has a refinery efficiency from 89.6% to 91.6% [97]. I take the average efficiency of 90.6% for conventional jet fuel refining process for simplicity. Synthetic fuel will cost $\frac{90.6\%}{39\%}$=2.32 times of energy to deliver the same amount of energy to conventional air fuels under direct air capture and $\frac{90.6\%}{47\%}$=1.93 times of energy under concentrated input. Taking the current average energy consumption of 0.5 kWh per passenger-kilometer for air transport with conventional fuels, using synthetic fuels on air transport will cost 0.97 to 1.16 kWh per passenger-kilometer. Therefore, the specific energy consumption of air transport will be $\frac{0.97}{0.06} = 16.2$ to $\frac{1.16}{0.06} = 19.3$ times higher than railway transport.

I also estimated the increment of total energy demand for Europe's air passenger under synthetic fuel scheme. The total passenger-kilometers by air in 2017 were estimated as 1116 billion passenger-kilometers, as presented in Method Description 3 in Appendix – Descriptions of analysis. Therefore, using synthetic fuels will likely increase the energy demand by 558 TWh[i] to 736.56 TWh[ii], compared to air transport with conventional fuels. Final energy consumption[iii] in the E.U. in 2018 was 10920 TWh [98]. Hence, the increase in energy demand for air transport after switching to synthetic fuel will add around 5% to 7% of the E.U.'s annual final energy consumption.

Such results widen the gap between air and rail transport. Under the assumption that synthetic fuel's production uses completely carbon-neutral electricity, air transport's energy consumption under synthetic fuel scheme to fulfill the same passenger demand between point A and point B will be much higher than the railway. From railway routing results that I derived from raildar.fr for high volume flights, I have

[i] $\frac{(0.97-0.5)kWh}{pkm} \cdot 1116\ billion\ pkm = 558\ TWh$

[ii] $\frac{(1.16-0.5)kWh}{pkm} \cdot 1116\ billion\ pkm = 736.56\ TWh$

[iii] Final energy consumption is the total energy consumed by end users, including private households, agriculture, industry, road transport, air transport (aviation), other transport (rail, inland navigation), services, and others.

estimated that railway travel takes around 1.42 times of distance as great circle distance. Therefore, with the assumption that flights follow great circle distance, railway transports take 1.42 times of air travel distance on average, indicating 1116 billion passenger-kilometers by air are equivalent to $1116 \cdot 1.42 = 1585$ billion passenger-kilometer by rail. Taking 0.06 kWh per passenger-kilometer as railway transport's specific energy consumption, 1585 billion passenger-kilometer by railway will consume 95.1 TWh[i] per year, accounting for only 7.3%[ii] to 8.8%[iii] of energy consumption as air transport under synthetic fuel scheme. Thus, railway transport will consume much less energy to carry the same number of passengers.

Arguably, the production of synthetic fuels can leverage the intermittency of renewable energy supply as the product can be stored for later usage. In contrast, railway transport's energy demand most likely will require an immediate response from the supply side. Nevertheless, the additional energy needed in synthetic fuel schemes imposes extreme challenges for the future energy supply, and railway transport also has options to implement energy storage systems to have flexible responses even under intermittent renewable scenarios.

Environmental impacts

From the perspective of carbon savings, synthetic fuel can significantly lower air transport emissions. The primary advantage of synthetic fuel is that its carbon cycle can be utterly carbon-neutral if the electricity for the entire production process is carbon-free with a renewable source for the feedstock CO_2 is exploited, such as direct air capture and biogenic CO_2 sources [91]. The carbon cycle is shown in Figure 5-2. Even under the most unsatisfactory situation where CO_2 emitted from airplanes using synthetic fuels is not captured, atmosphere's carbon volume is unchanged compared to the volumes before the carbon capture.

However, studies also indicated that air transport has more threats to global warming potential than CO_2 emissions. NOx, water vapor, sulphate aerosol, and soot aerosol can be considered as non-CO_2 impacts. In general, non-CO_2 impacts have a larger scientific uncertainty than the CO_2 impacts. Moreover, air transport may incur cirrus clouds that impose another uncertainty to aviation's non-CO_2 impacts [99-102]. Studies have defined a radiative forcing index factor that quantifies non-CO_2 impacts to CO_2-equivalent values. But the range of the radiative forcing index factor varies from 1 to 2.7, validating the argument that non-CO_2 impacts have a larger scientific uncertainty [101].

Although aviation's general global warming potentials of non-CO_2 emissions are rather complex, studies have thoroughly demonstrated that air transport has its intrinsic deficiencies against reducing global warming potentials.

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[i] $1585\ billion\ pkm\ \cdot 0.06 \frac{kWh}{pkm} = 95.1\ TWh$

[ii] $\frac{95.1\ TWh}{1.16 \frac{kWh}{pkm} \cdot 1116\ billion\ pkm} = 7.3\%$

[iii] $\frac{95.1\ TWh}{0.97 \frac{kWh}{pkm} \cdot 1116\ billion\ pkm} = 8.8\%$

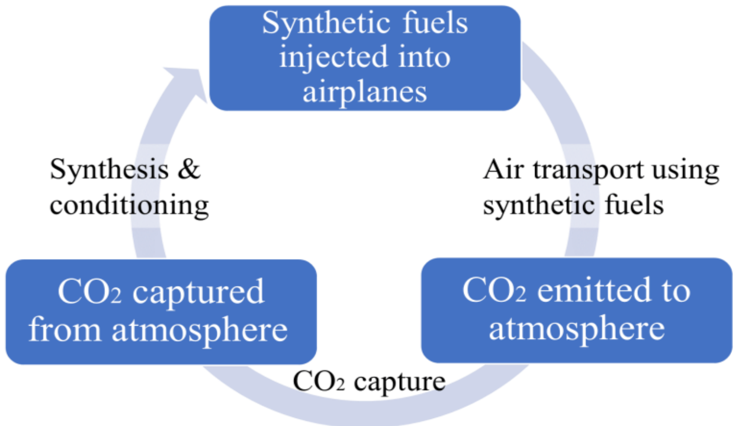

Figure 5-2 Carbon cycles of synthetic aviation fuels.

On the other side, railway transport has shown its low carbon emissions in operations with an average of 27.7 g CO_2 per passenger-kilometer, as shown in Table 1-2. Considering the increasing electrification rate of Europe's railway networks and a growing ratio of renewable energy supplying to the railway system, it is likely that the railway's carbon intensity will drop further. Hence, in comparing environmental impacts, it is expected that railway transport will have fewer impacts relating to climate change.

Summary

From the perspective of energy consumptions, the introduction of synthetic fuels to air transport will lead to 16.2 to 19.3 times of energy consumptions per passenger-kilometer to railway transport. Such a considerable difference implies that railway transport requires much less electricity, imposing significantly lower demands on the grid and generation utilities.

From the viewpoint of environmental impact, supplied by carbon-free electricity and CO_2 from air or biogenic sources, synthetic jet fuels can significantly decrease air transport emissions. Nevertheless, air transport has other climate change effects, causing additional uncertainties to global warming potentials and giving air transport competitive disadvantages. Even at current stages where many trains are diesel-powered, railway shows its environmental advantages to air transport. Therefore, after comparing energy efficiencies and environmental impacts of both air transport with synthetic fuels and railway transport, I derived the conclusion that in the long run, railway transport may still be the winner for its advantages on both dimensions.

Section 5.2 Railway's chances and challenges in the long run

Compared to Chapter 4's conclusion that overnight sleepers do not show significant prospects on carbon reductions at current stages, the last section's discussion about energy efficiency and environmental impact tells a different story for the potential of overnight sleepers and railway transport. In comparison with railway transport, synthetic fuels will significantly increase air transport energy consumption with no advantages in reducing global warming potentials. Therefore, I have concluded that railway transport has a competitive advantage over air transport with synthetic fuels in the long run.

Based on that railway transport should be prioritized in short-haul transport in the long run, I present this section's discussions on further possible improvements for a cleaner and more efficient railway transport.

Subsec. 5.2.1 Reduction of environmental impacts

In the short term, as diesel propulsion is still a key source powering trains, railway transport is still entangled with particulate matters and NOx emissions [27]. Admittedly, modern diesel multiple units and locomotives produce fewer pollutants. A non-diesel railway system must be endorsed for the complete elimination of such contaminants.

Consequentially, railway electrification is happening in Europe. Another concern arises from electricity sources to supply the energy demand for railway transport. Figure 5-3 provides a reference for carbon intensities of different power sources on railway transport. It indicates that the electrification of railway transport needs to be accompanied by renewable energies to deliver ultra-low, even zero carbon emissions. When the higher electrification rate of the railway grows, it is also essential to monitor the carbon intensity of electricity transmitted to the railway networks. Different countries have different electricity carbon intensities from different electricity mixes. While Sweden had a carbon intensity of consumed low voltage electricity as low as 47 g CO_2 per KWh in 2013, EU28's average was 447 g CO_2 per KWh consumed [i][103]. Compared to electricity generation's carbon intensity in 2013, the latest data revealed that electricity generation's average carbon intensity in 2019 has dropped 15.6% [104]. Therefore, I am optimistic about further reductions of carbon intensity in the entire electricity generation and transmission value chain.

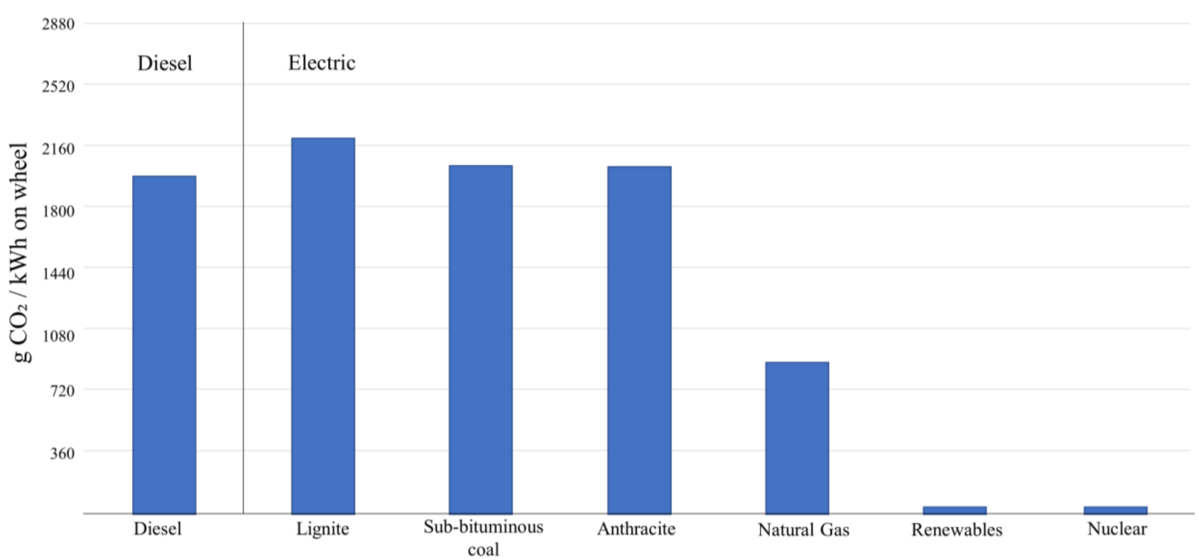

Figure 5-3 Average well-to-wheel carbon intensities for diesel powertrains, compared with electric powertrains using various primary sources, modified from [105].

In the long run, as the E.U. has set the target of reaching net-zero greenhouse gas emissions in the energy sector and Europe has an increasing trend of railway electrification, it is anticipated that electricity's carbon intensity will decrease further, to zero in the most optimal cases [106].

This subsection's discussion verifies the conclusion in Section 5.1 that railway transport will create a broader gap in carbon and carbon equivalent emissions to air transport with the help of both increasing supplies of renewable energies and increasing electrification of railway transport in Europe.

[i] Appendix Table 4 presents the full list of carbon intensities of EU28.

In addition to particulate and greenhouse gases, several categories of noises can be created with passenger trains, including rolling noise, traction noise, and aerodynamic noise [107]. Besides, pantograph noise is very particular for electric trains, especially high-speed trains [32]. Considering the fleet of electric trains is growing because of the increasing electrification rate within Europe, necessary measures for reducing different types of noises are required.

Several types of measures may be implemented to reduce railway transport's noise levels:

- Technical advancements can effectively reduce the overall noise level of railway transport. For instance, porous covers can reduce the aerodynamic noise of pantographs [32, 108].
- The schedule arrangement for overnight sleeper services should be adjusted to avoid noise disturbances in densely populated areas.

Subsec. 5.2.2 Extended travel ranges of railway services

In this thesis, I have mainly studied the potential of normal speed railway services that generally operate below 100 km per hour because of the limited connectivity of existing high-speed railway networks, as discussed in Chapter 1. Nevertheless, Section 4.5 has analyzed that normal speed overnight sleepers have an upper limit of passenger base accounting for 17% of all domestic and intra-Europe air passengers. Current overnight sleeper services have an average travel range below 1000 kilometers per service while 53% of the domestic or intra-Europe flights traveled more than 1000 kilometers, based on Eurostat's derived data. Therefore, for a modal shift in the long run, normal overnight sleepers alone may not be able to satisfy the demand and reduce the environmental impact effectively. I propose that a well-connected high-speed railway construction plan shall be evaluated for the modal shift from air transport to railway transport.

Existing overnight high-speed railway services are already in operation for years, especially in China. For instance, Beijing's overnight sleeper services to Guangzhou travel more than 2000 kilometers within 13 hours with that each service can carry over 500 passengers [70]. The cases of current mature overnight high-speed services leave a large space for imagination that well-connected high-speed railway networks will boost the overnight high-speed railway services.

Furthermore, a well-connected high-speed railway network will enhance the replaceability of overnight sleepers to air transport as it can cover longer travel distances over the same travel times. Figure 5-4 presents five circle maps representing five cities in various geographical locations in Europe when setting 2000 kilometers as the radius. It is relatively clear to see that if a high-speed railway network can serve around 2000 kilometers of direct-line services in overnight sleepers, most Western European cities can be within reach of Eastern Europe. In the figure, Bucharest and Riga are cases where both cities are less than 2000 kilometers away from Paris, Amsterdam, Frankfurt am Main, and Milan. In Italy, Spain, and the United Kingdom, the reach of their international connectivity of high-speed railway may be restricted because of their landscapes. Nevertheless, in the majority area of continental Europe, a well-connected high-speed railway network can expand the market of modal shift from air transport to overnight sleepers. A high-speed railway network can also enhance the connectivity between Western Europe and Eastern Europe, improving the asymmetry that I have discussed in Section 4.6.

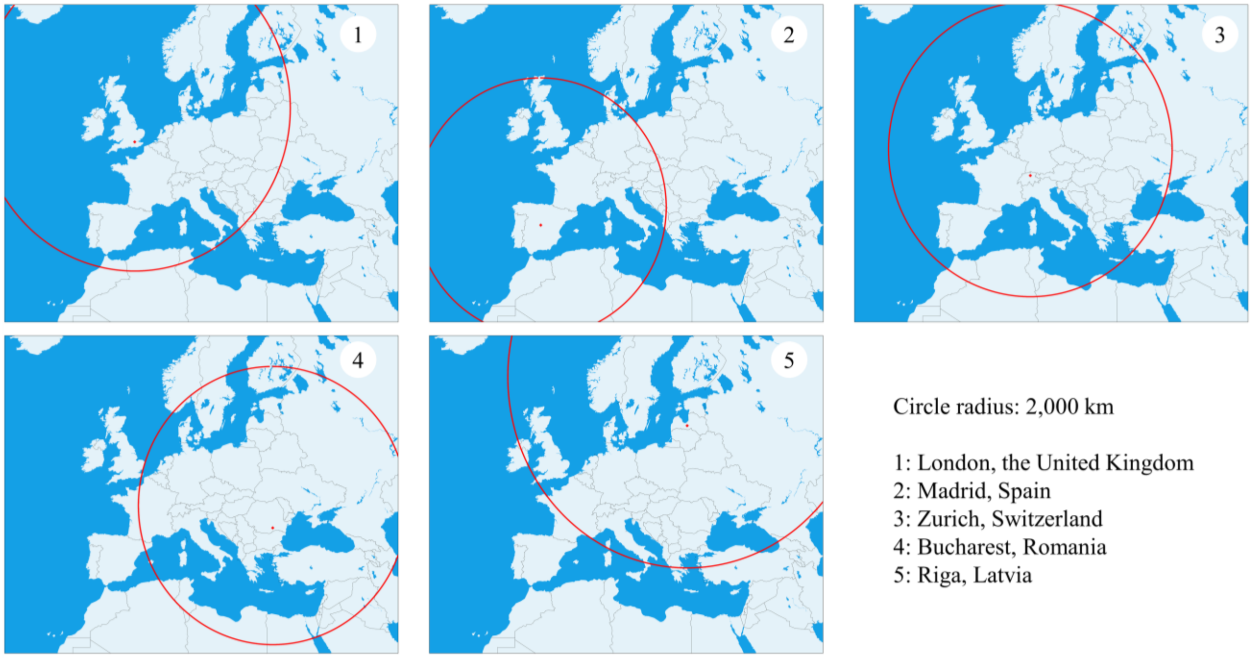

Figure 5-4 Circle maps with a radius of 2,000 kilometers for five selected cities in Europe.

In Subsec. 4.1.1, I have suggested that trains running at different speeds will impose high pressures on railway operators' schedule arrangement. With a well-connected high-speed railway network, the issue of schedule arrangement for different travel speeds will also be alleviated as high-speed railway will have separated operating networks without interfering with the operation of normal speed trains. Consequentially, more passengers can be shifted from air transport, furtherly reducing air transport's environmental impacts.

Section 5.3 Summary and implications in the long run

In Section 5.1 and Section 5.2, I have discussed the pros and cons of railway transport and air transport in short-haul passenger transport in the long run based on the assumption that electricity will be generated from renewable sources.

In the long run, the transport sector is closely linked with the energy sector as the energy sector's carbon intensities to produce fuels and electricity in different transport modes will determine the transport modes' carbon intensities. Evidence has been found that coal-electrified railway has higher emissions than diesel-powered railway and that renewables can power railway transport nearly carbon-free. Hence, carbon-free energy supplies to the transport sector will be the prerequisite for a carbon-free transport future. Under synthetic fuel's scheme for air transport, clean energy will also be a requirement for obtaining a carbon-neutral cycle.

Among the two modes of transport, air transport is expected to have more changes in the long run. Studies have revealed that synthetic fuels will likely be the prioritized solution for air transport to replace current conventional kerosene, which has caused immense carbon emissions. In optimal cases, air transport using synthetic fuels produced from clean energy will be carbon-neutral. Nonetheless, due to air transport's uncertainties brought by other non-CO_2 impacts, air transport's global warming potential is hard to be neutralized even when the production of synthetic fuels can be carbon-neutral. Furthermore, synthetic fuels' production costs higher energy compared to conventional oil extractions and refining, and it will lead to extremely high energy consumption per passenger-kilometer compared to the status quo.

On the other hand, railway transport has shown advantages on both environmental impact and energy consumption. Under the same clean energy supply sources as air transport, railway transport does not have additional global warming potentials as air transport does. Also, railway transport's energy consumption per passenger-kilometer is expected to be stable and even decreasing in the future.

Therefore, this chapter has indicated that in the long run, railway transport's competitiveness has changed. With air transport's extremely high energy consumption ahead and remaining global warming potentials despite its decarbonization efforts, railway transport is suggested to be prioritized in short-haul passenger transport. Normal speed overnight sleepers have an upper passenger limit. Therefore, modal shift from air to rail should consider more railway transport options, such as high-speed railway and the combination of high-speed railway with overnight sleepers. However, current scope of study is not enough to form an executable plan. Further studies are suggested to provide detailed railway displacement strategy for a decarbonized short-haul passenger transport from technological, environmental, economic, and political perspectives.

Chapter 6 Conclusion and future works

Through discussions of previous chapters, I conclude this study as such:

In 2019, flights served over 600 million passengers in short-haul travel in Europe. High-speed railway services are available in certain routes with high passenger volumes but not all over Europe because of their limited connectivity. Currently, overnight sleeper is a minor player with only 5 million to 30 million passengers served annually.

Both patterns of short-haul air passenger flows and railway infrastructure networks are observed with asymmetry between Western Europe and Eastern Europe. Almost all high-volume flight corridors are within Western Europe. To integrate the mobility between Western Europe and Eastern Europe, higher investments and more favorable strategies should be proposed to improve public passenger transport in Eastern Europe.

As railway transport shows huge advantages in terms of environmental impacts, especially in short-haul travel, I have studied the feasibility of a partial modal shift from short-haul flights to overnight sleepers. Based on that travel demands in Europe are proxied by air passengers and a passenger split between overnight sleepers and flights in proposed new overnight sleeper routes, I observed that effects of decarbonization of the transport sector are rather negligible by partially modal shift from flight to overnight sleepers. Since potential overnight sleeper routes have high passenger volumes and appropriate travel times, these filtered routes may still be considered as routes with business potential for railway operators.

In the long run, I have derived different insights as air transport has limited options to decarbonize because of its long lifecycles of existing infrastructures and aircraft and its engine technologies. Synthetic fuels have been regarded as the most promising replacement for conventional fossil fuels. The production of synthetic fuels can be carbon-neutral if all energies in the production process are carbon-free. Nevertheless, the drawbacks of synthetic fuels in aviation have been concluded as vital. The introduction of synthetic fuel will impose extremely high energy consumption in the production process. Besides, despite the use of carbon-neutral fuels, air transport has other non-CO_2 impacts that can impose global warming potentials that may be even higher than CO_2. Therefore, in the long run, I have reviewed the opportunities for railway transport in short-haul transport. Railway transport's specific energy consumptions in passenger-kilometers are relatively stable with down-going trends and the potential to have almost carbon-free operations. With the higher market share of renewables in the energy market, railway transport will likely have fewer carbon intensities in its operations.

After comparisons between two transport modes in both short-run and long-run, I conclude that immediate modal shift from air transport to overnight sleepers has negligible decarbonization effects as current railway infrastructures have limited capacities, and only a small portion of existing flight passengers can be shifted to the railway. In the long run, railway transport is of advantage in both environmental impacts and energy efficiency. Therefore, implications have been that long-term investment in railway transport will provide a better basis for sustainable short-haul passenger travel in Europe. A higher ratio of investment should go to Eastern Europe to alleviate the asymmetry of railway infrastructure conditions. Nevertheless, railway transport requires more than one transport options for short-haul passenger transport because short-haul transport is a large and growing market and the overnight sleeper alone has limited servicing capacity. By discussing the potential of high-speed railway and the combination of high-speed railway and overnight sleepers, I have shown that a well-connected high-speed railway network will be able to cover farther ranges than the overnight sleeper alone.

Based on this study's discussions and conclusions above, I propose the following directions to investigate the idea of modal shift from air transport to overnight sleeper services and more general railway transport.

As two business models are identified through this study and only the possible high-passenger volume overnight sleeper services are studied, I suggest exploring the rationale behind current operating overnight sleeper services, particularly those do not have high air passenger volumes. Study results of niche services will help predict future travel demands that can be satisfied by railway transport and consequentially provide guidance to railway infrastructure planning.

Various causes have led to the passenger volume asymmetry between Western Europe and Eastern Europe. Hence, I suggest the investigation of green methods to improve Eastern Europe's public transport connectivity for a more integrated Europe. Besides, faster economic growth in Eastern Europe will bring higher mobility for Eastern European residents, requiring more investments in Eastern Europe. I have proposed an initial direction with different deployment strategies for Western and Eastern Europe to help Western Europe use more environment-friendly transport modes to re-distribute existing air travelers and help Eastern Europe prepare for its future demand growth in short-haul travels. From that point on, I suggest further specialized research on the transport investment strategy in Eastern Europe to fulfill multiple goals, including integrating Western Europe's transport network, meeting future travel demands, and reaching the emissions target.

The most important work in the future is analyzing the most suitable railway transport combinations for displacing short-haul flights as railway's advantages in the long run have been clearly demonstrated. Normal speed overnight sleepers alone cannot cover all short-haul flight passengers. The analysis should cover technological, environmental, economic, and political perspectives for available railway replacing choices. The result of the investigation should provide better visibility of overnight sleeper's role in decarbonizing short-haul passenger transport in the long run.

Although further studies shall be carried out to solidify this study's results, I have demonstrated that railway transport, in general, will be essential tools to decarbonize short-haul travel mainly carried by air transport in the long run because of their high energy efficiency and low environmental impacts. Overnight sleepers have the potential to partially displace short-haul flight passengers. Nevertheless, effectively reducing the environmental impact of air transport asks for a synergy of different railway options. Further studies are expected to prove this study's conclusion and bring more clear conclusions on this specific modal shift in the short-haul passenger transport sector.

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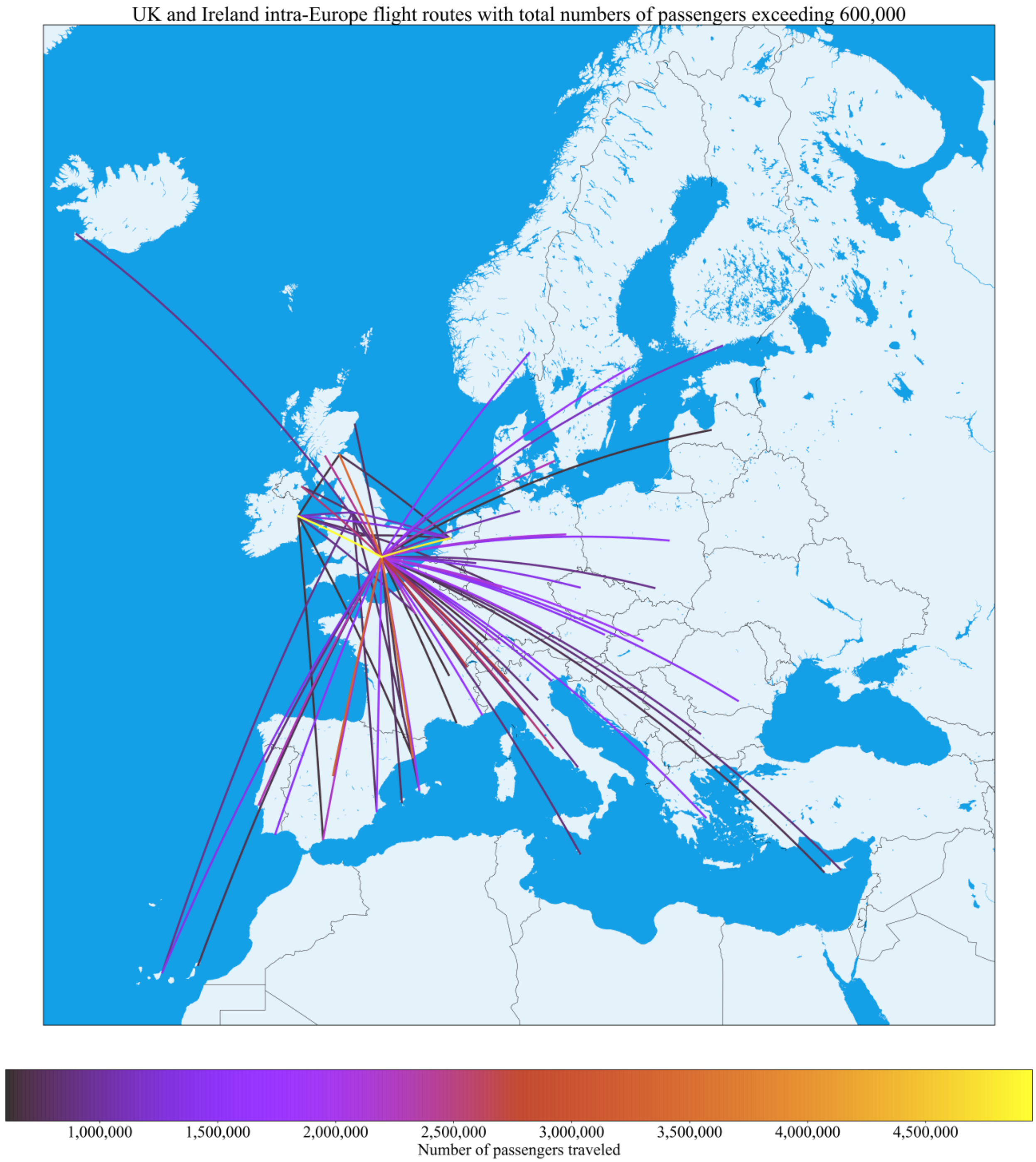
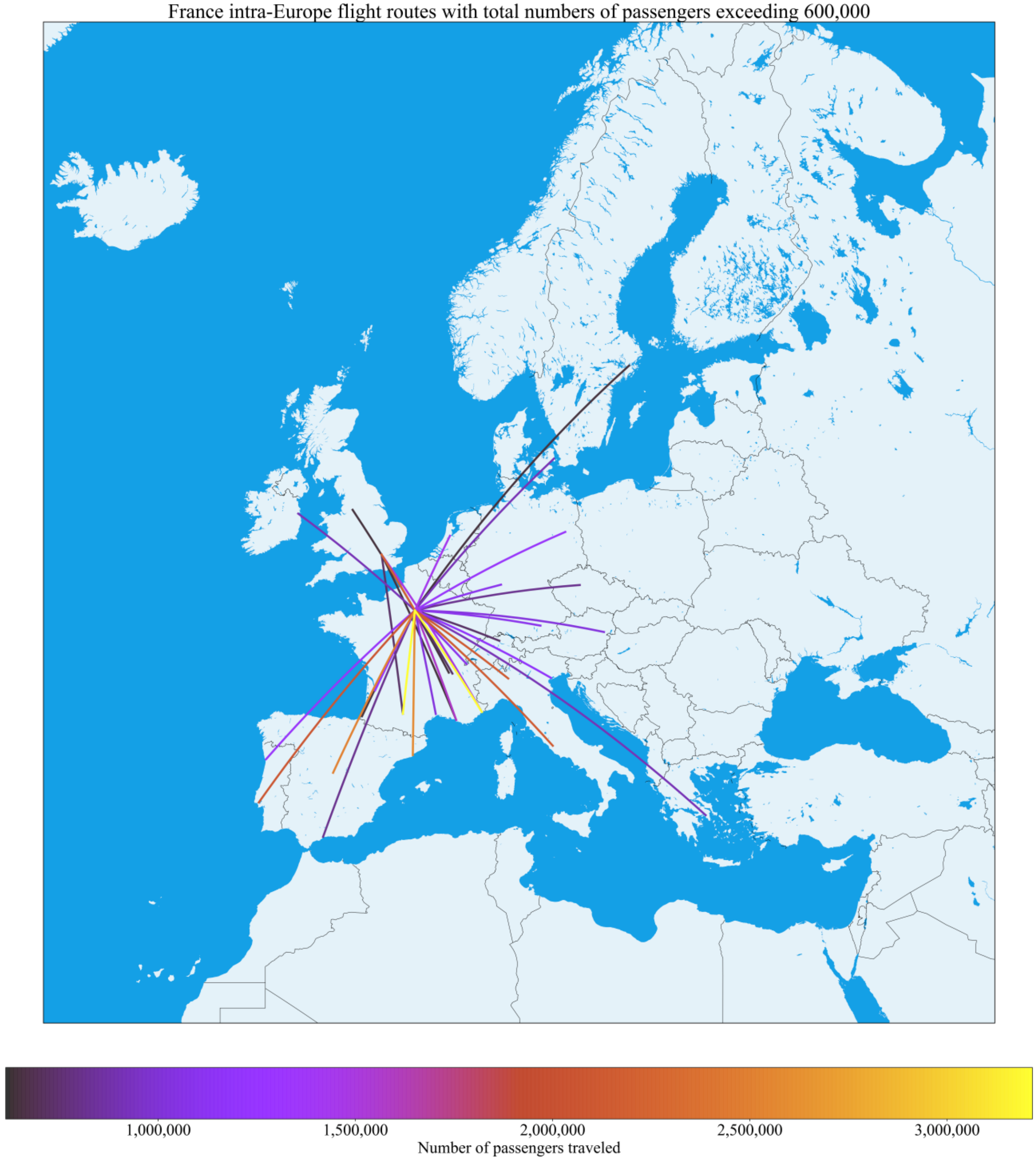
Appendix – Figures

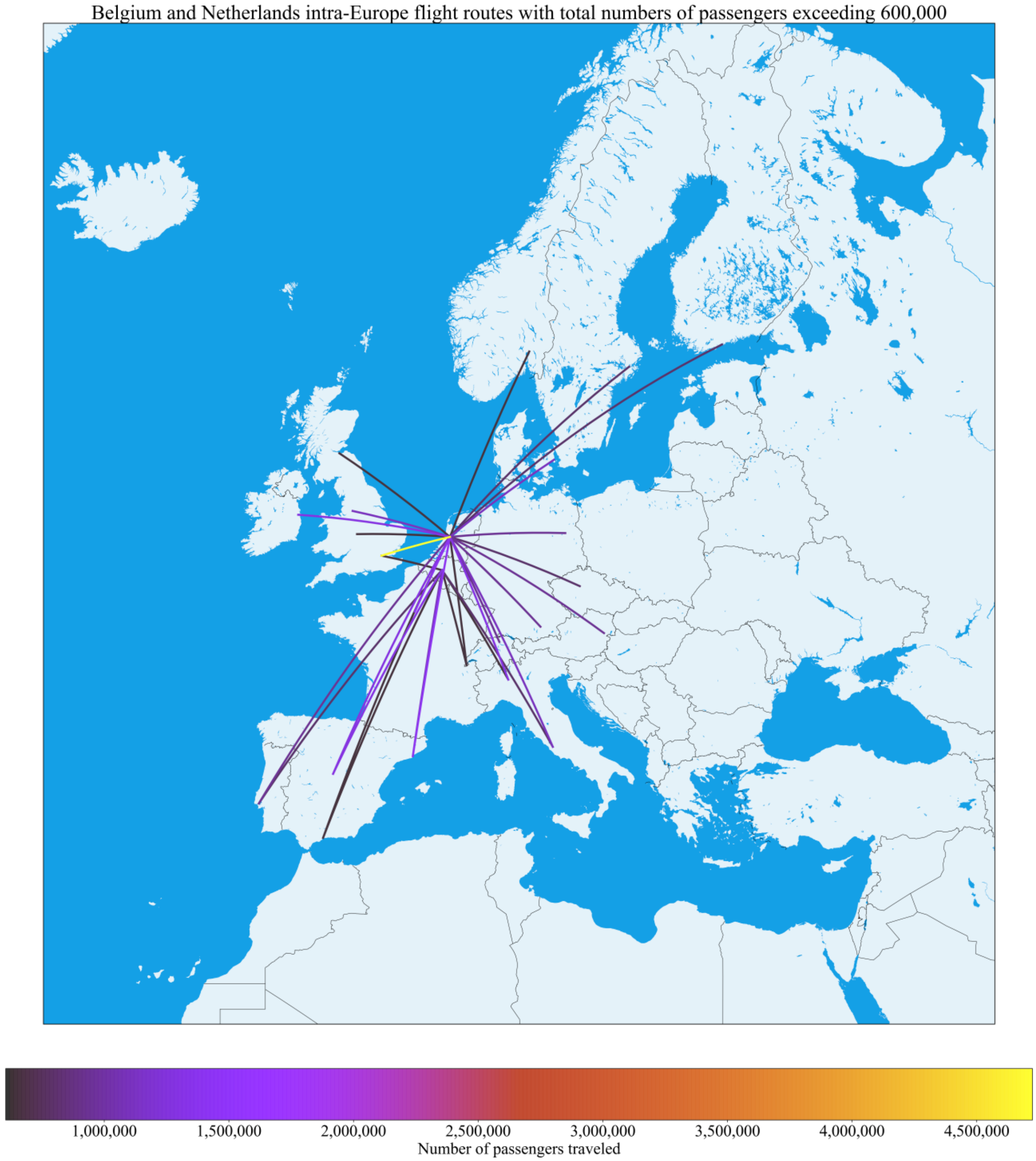


Appendix Figure 1 Visualization of intra-Europe flight routes involving the U.K. and Ireland with total numbers of passengers exceeding 600,000. The projection of the map is Mercator projection (preserving the angles).

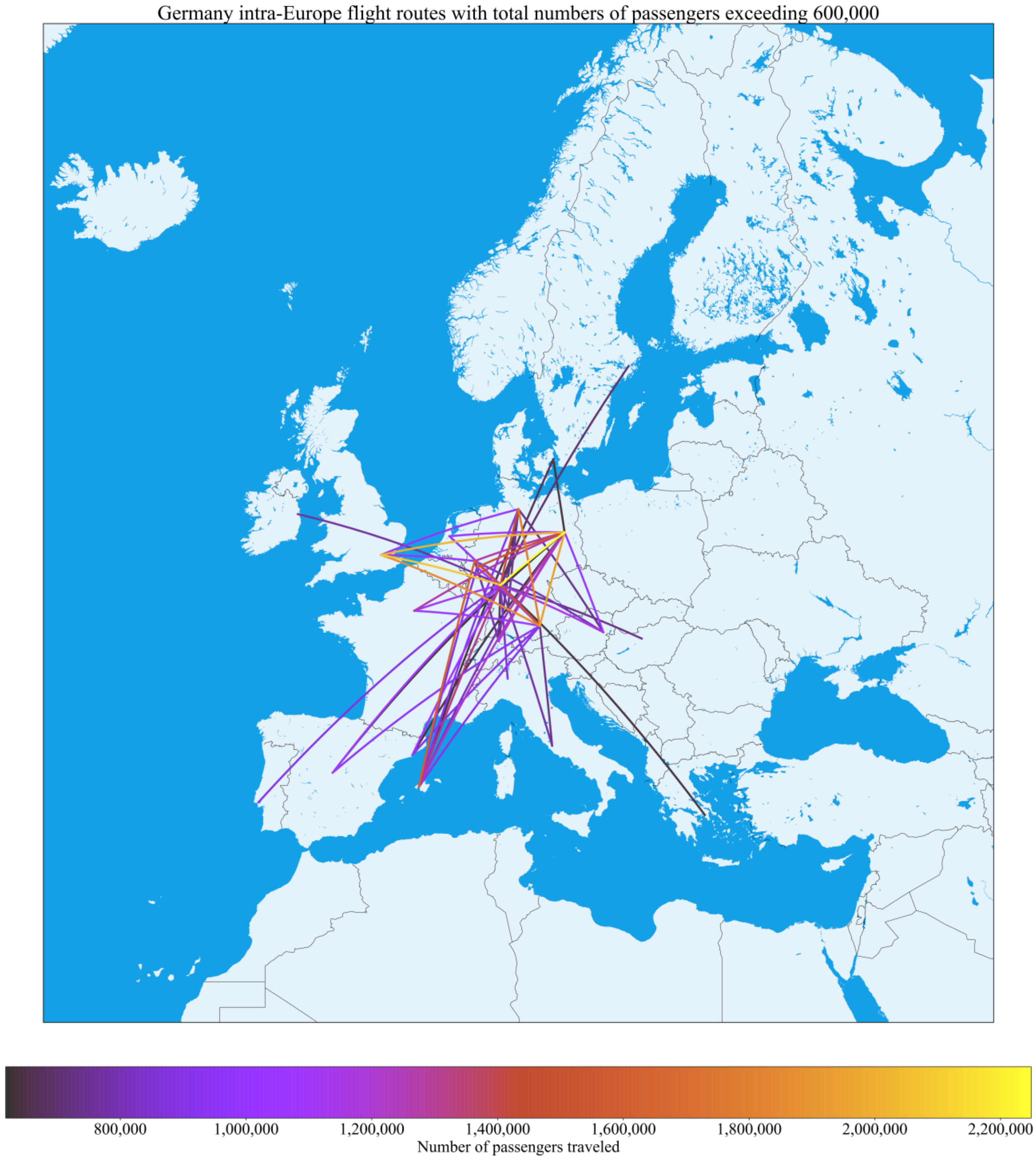
France intra-Europe flight routes with total numbers of passengers exceeding 600,000



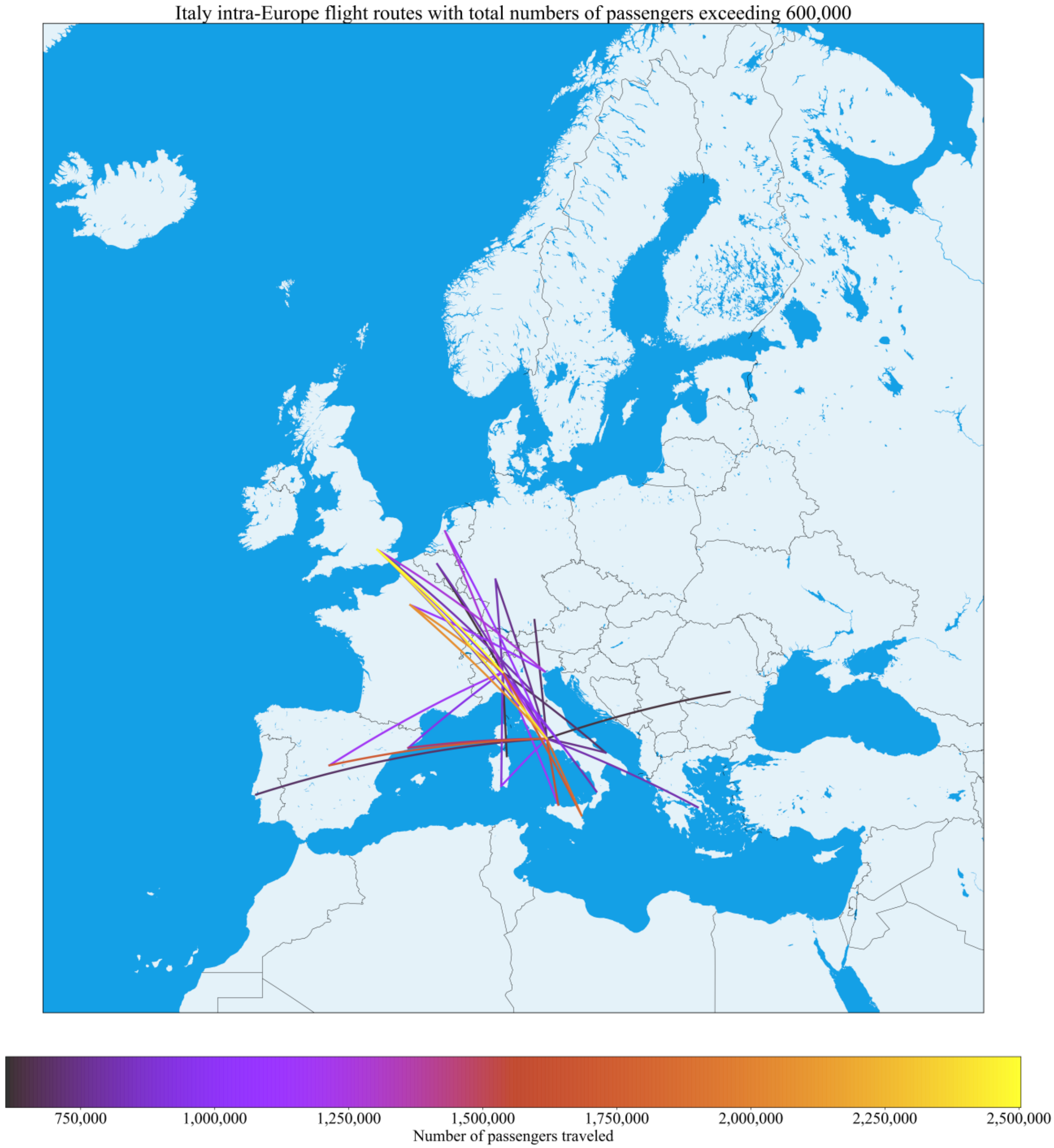
Appendix Figure 2 Visualization of intra-Europe flight routes involving France with total numbers of passengers exceeding 600,000. The projection of the map is Mercator projection (preserving the angles).



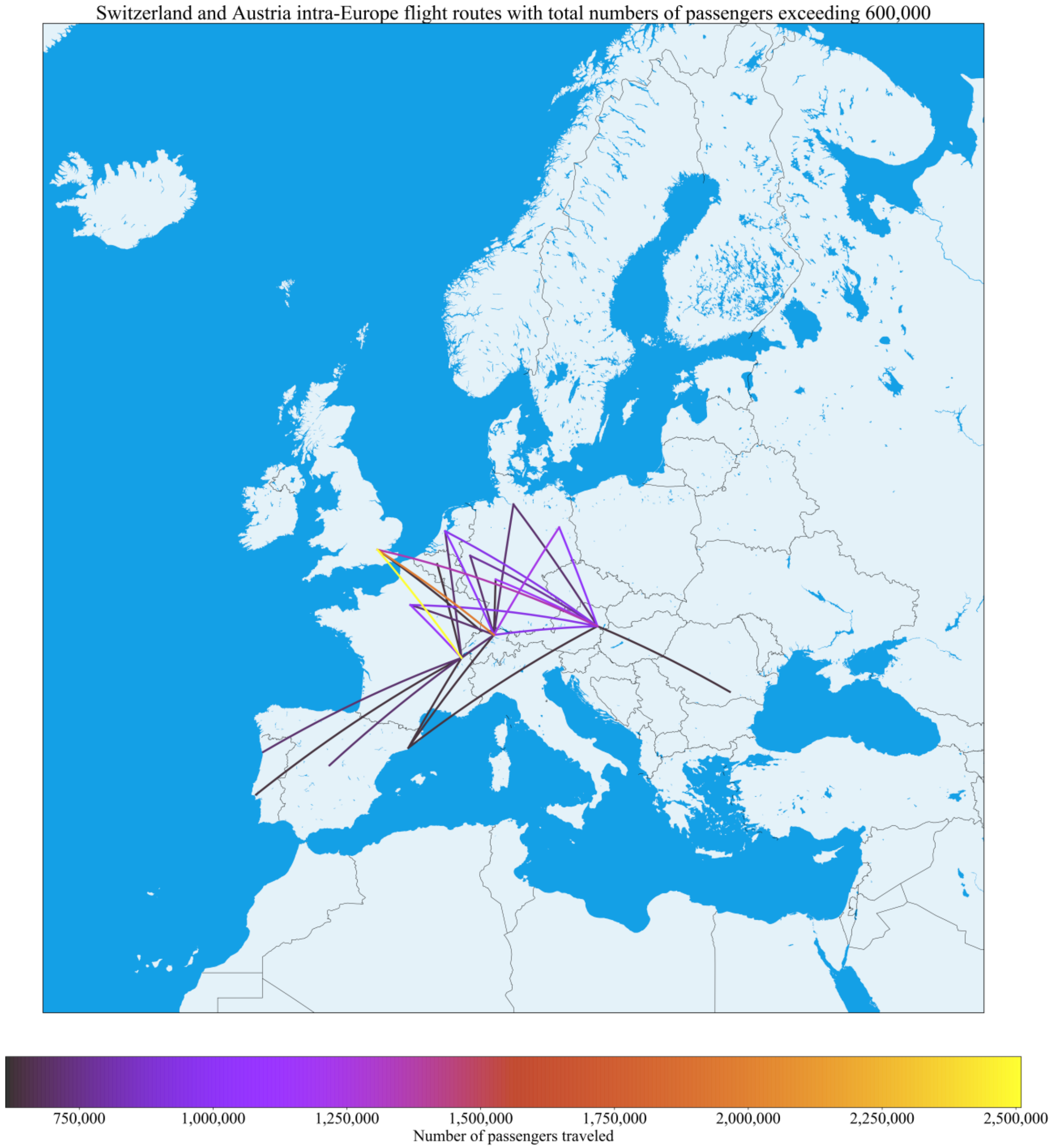
Appendix Figure 3 Visualization of intra-Europe flight routes involving Belgium and Netherlands with total numbers of passengers exceeding 600,000. The projection of the map is Mercator projection (preserving the angles).



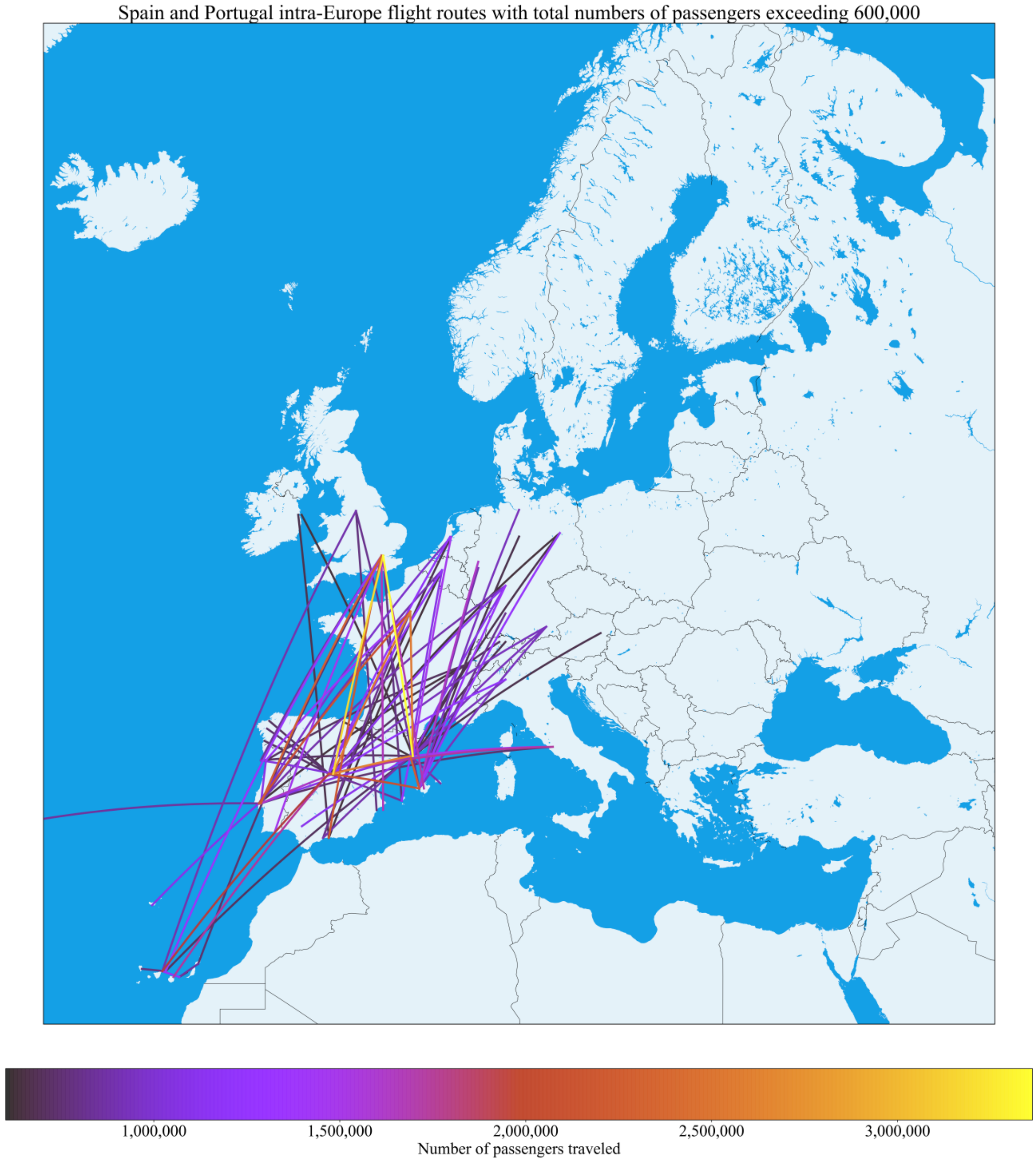
Appendix Figure 4 Visualization of intra-Europe flight routes involving Germany with total numbers of passengers exceeding 600,000. The projection of the map is Mercator projection (preserving the angles).



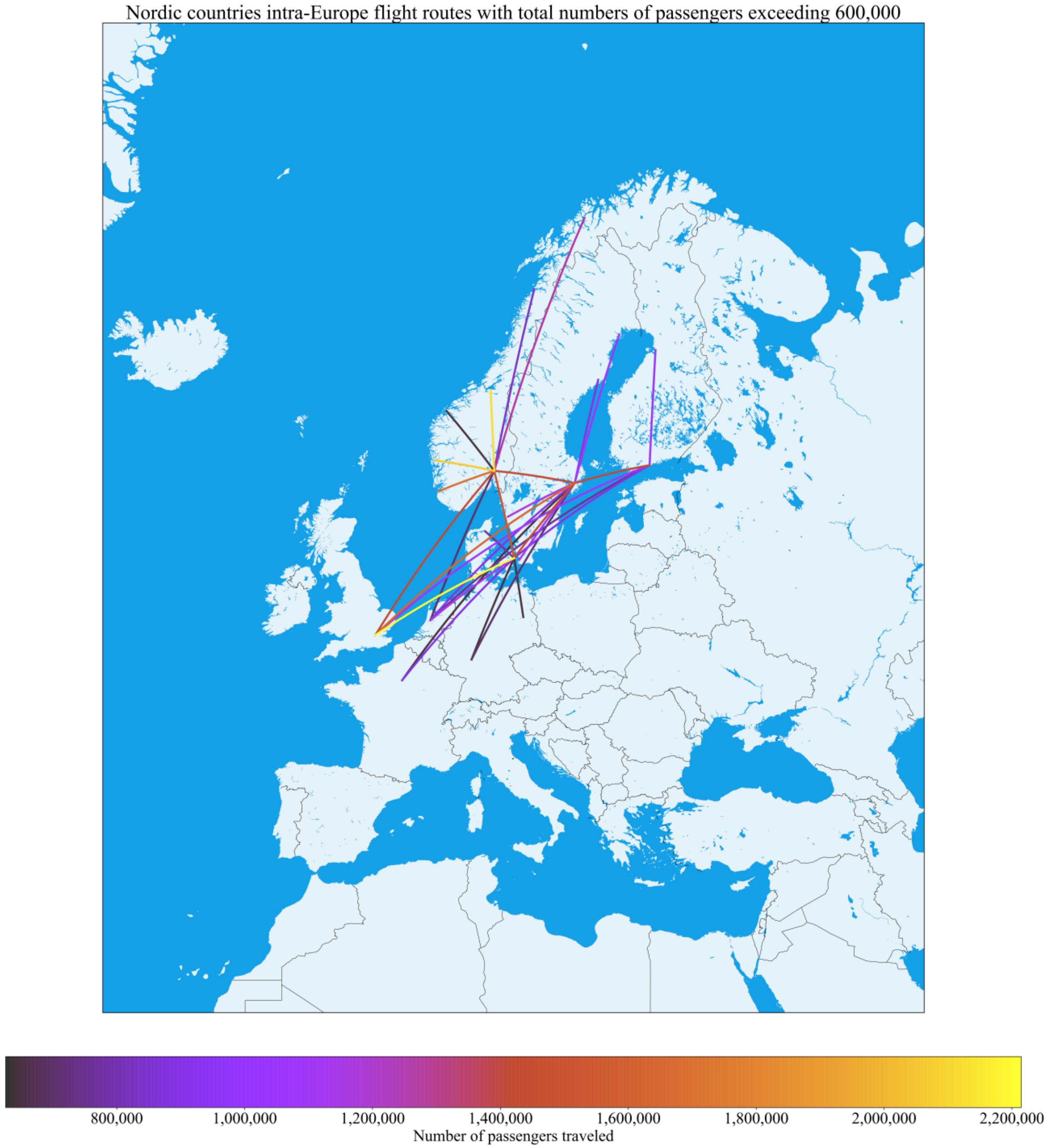
Appendix Figure 5 Visualization of intra-Europe flight routes involving Italy with total numbers of passengers exceeding 600,000. The projection of the map is Mercator projection (preserving the angles).



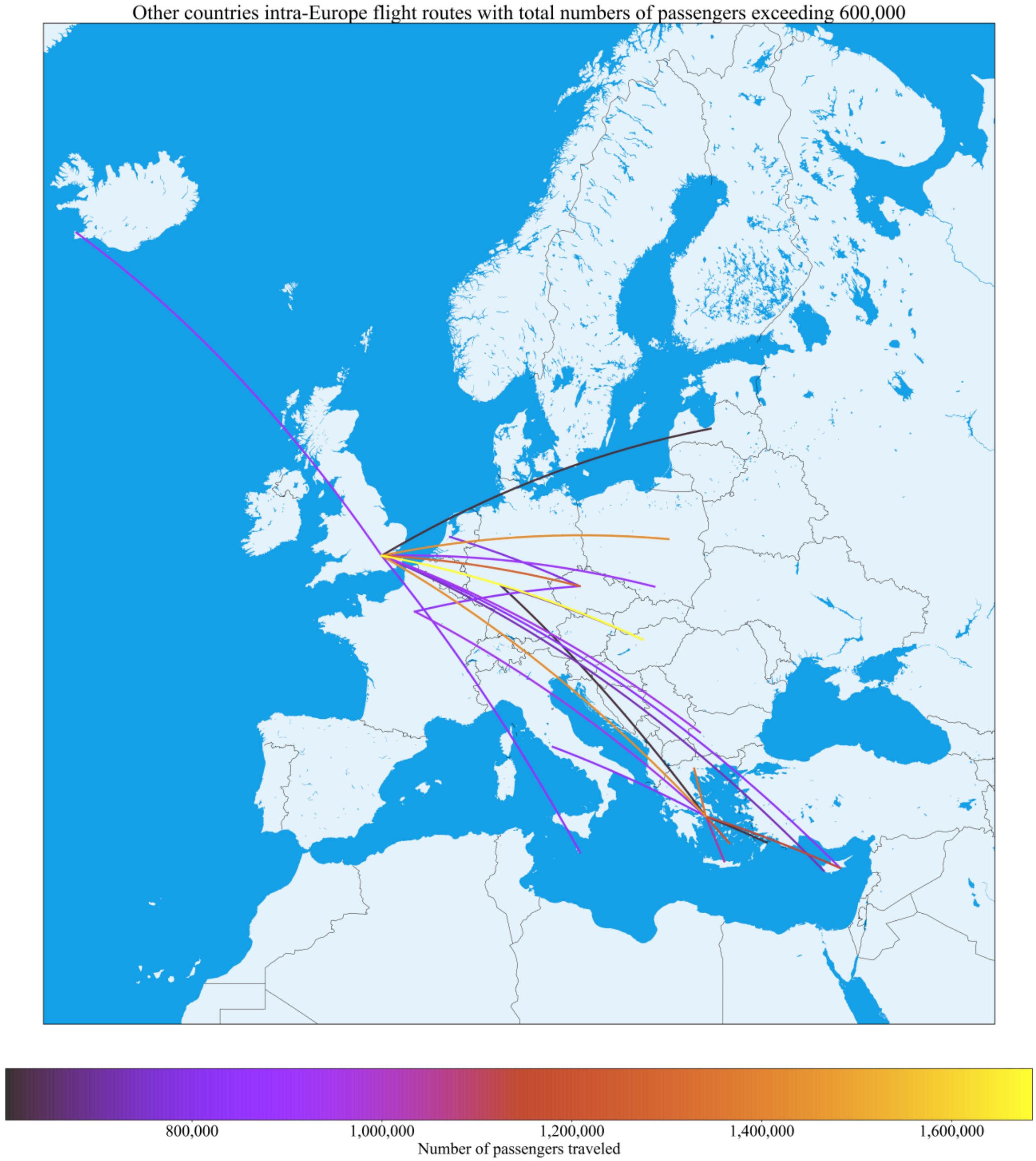
Appendix Figure 6 Visualization of intra-Europe flight routes involving Austria and Switzerland with total numbers of passengers exceeding 600,000. The projection of the map is Mercator projection (preserving the angles).



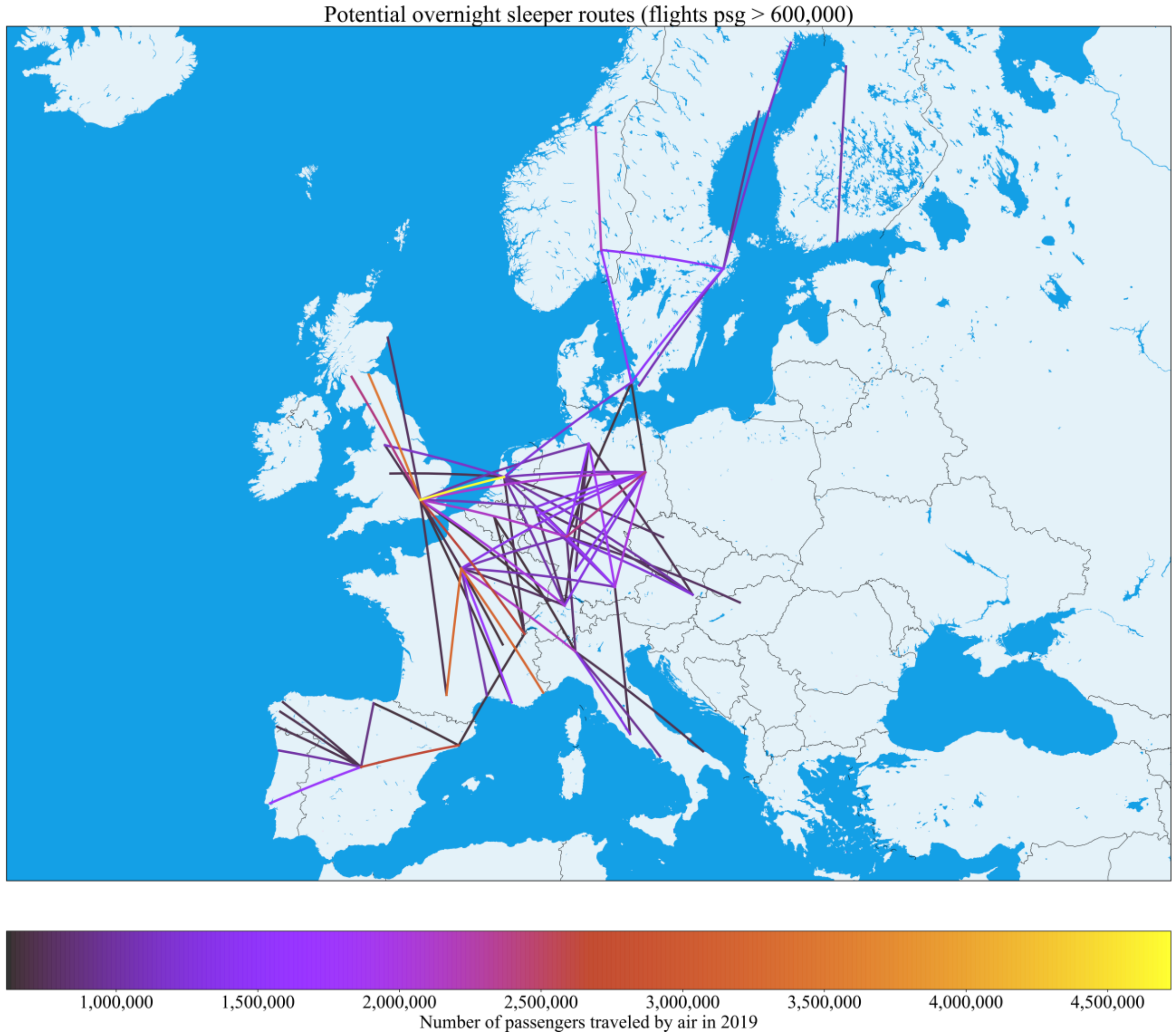
Appendix Figure 7 Visualization of intra-Europe flight routes involving Spain and Portugal with total numbers of passengers exceeding 600,000. The projection of the map is Mercator projection (preserving the angles).



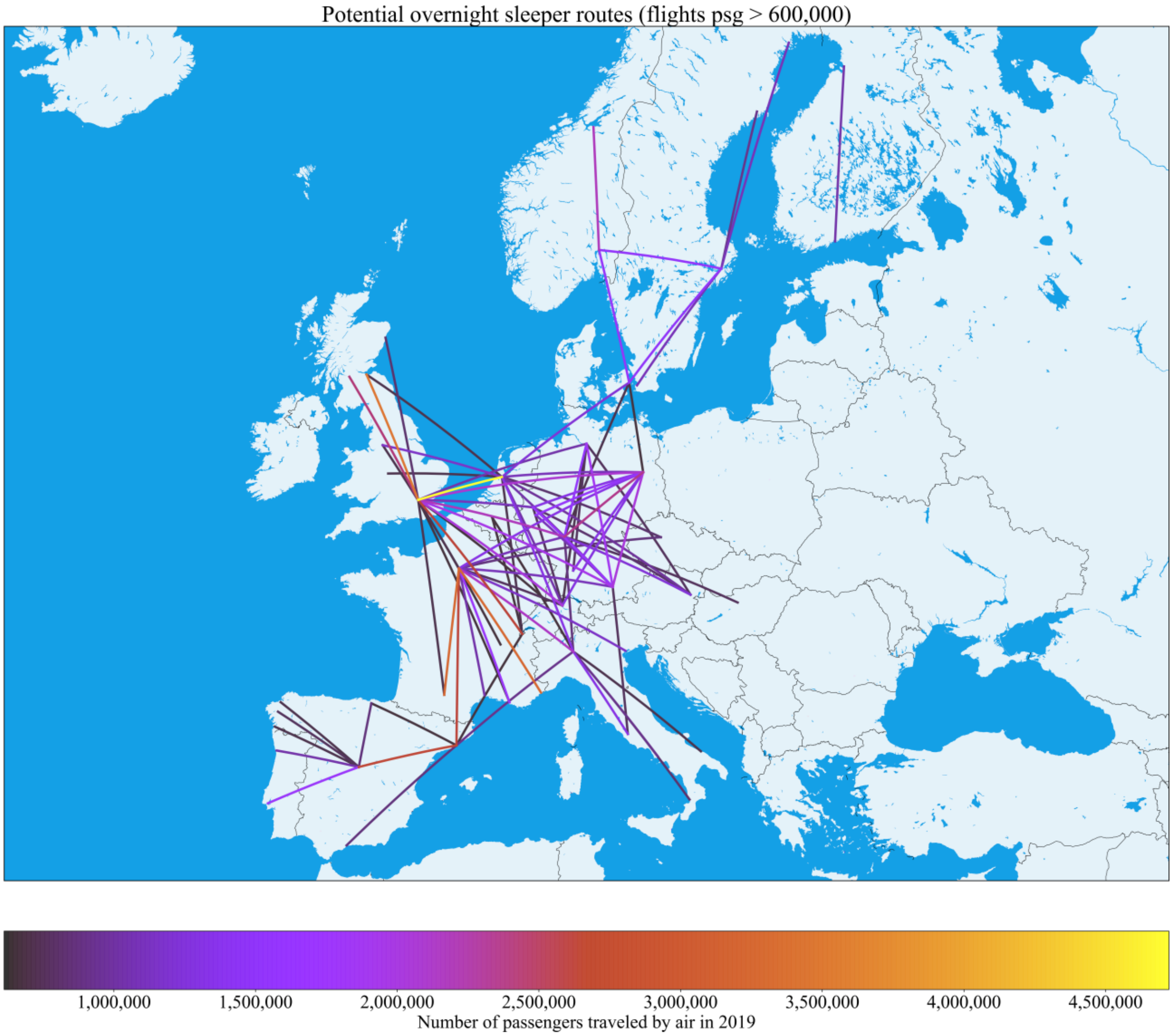
Appendix Figure 8 Visualization of intra-Europe flight routes involving Nordic countries with total numbers of passengers exceeding 600,000. The projection of the map is Mercator projection (preserving the angles).



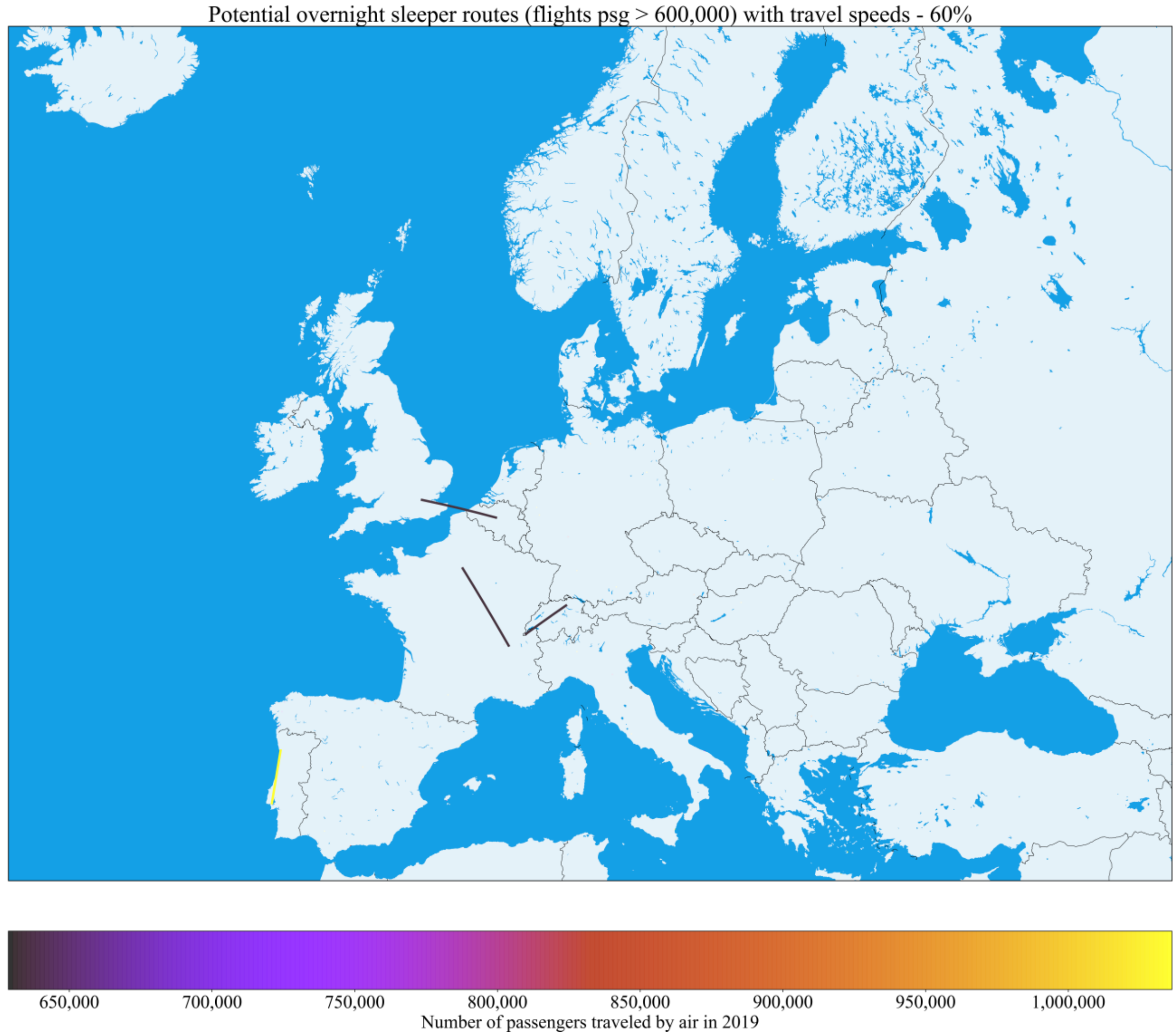
Appendix Figure 9 Visualization of intra-Europe flight routes involving other countries with total numbers of passengers exceeding 600,000. The projection of the map is Mercator projection (preserving the angles).



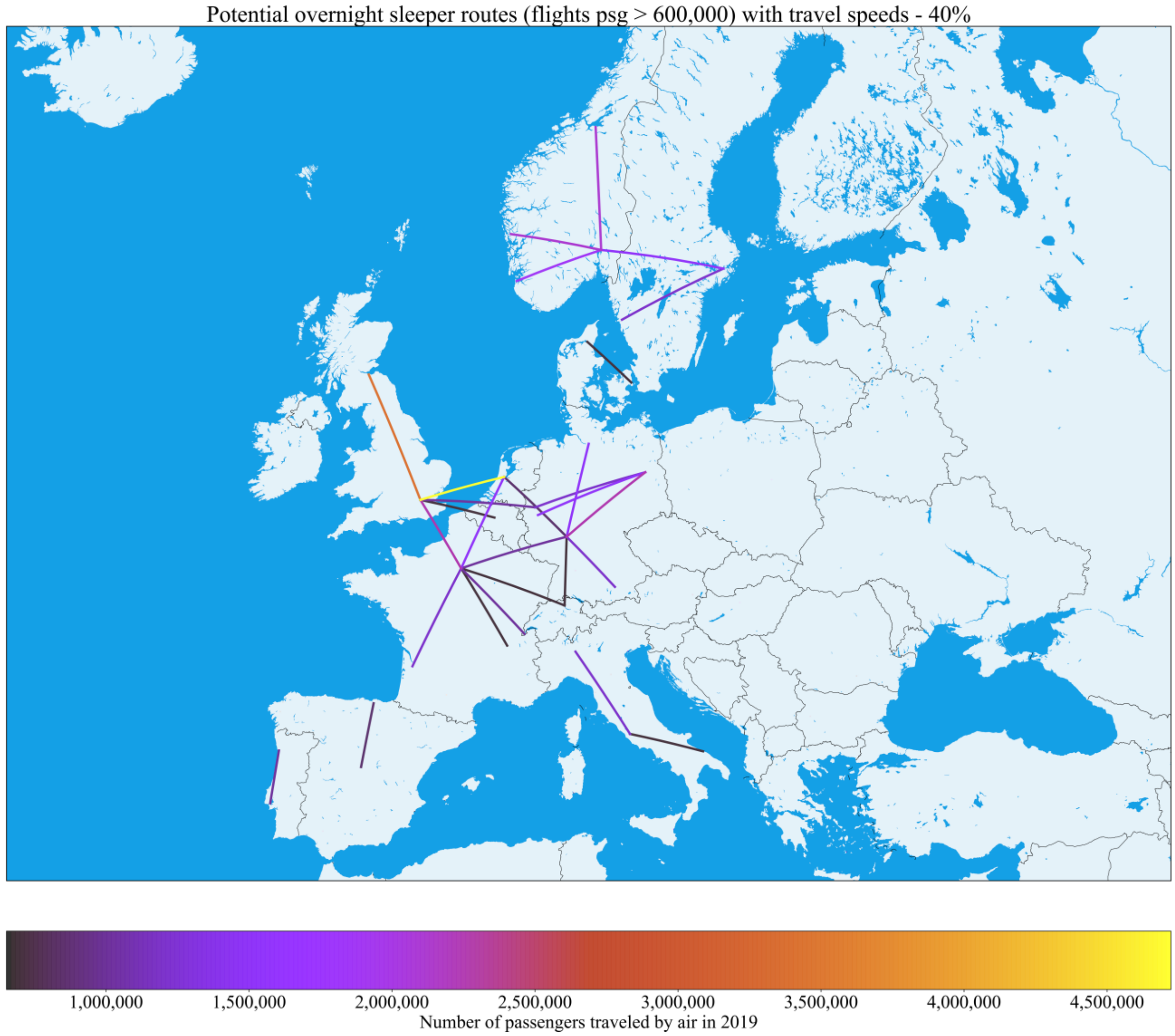
Appendix Figure 10 Overnight sleeper's potential routes (>600,000 flight passengers in 2019) within 7 to 14 hours of travel times.



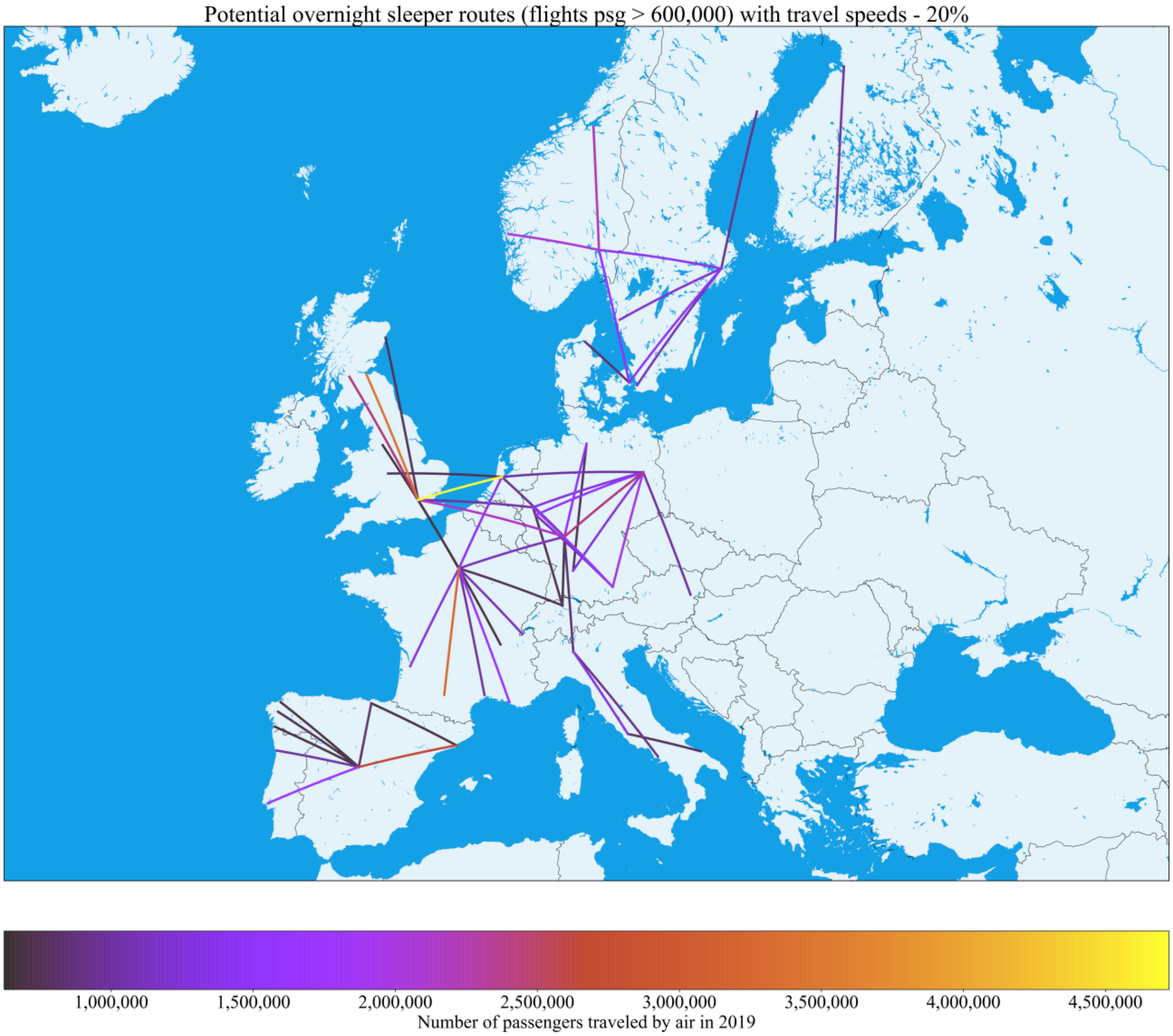
Appendix Figure 11 Overnight sleeper's potential routes (>600,000 flight passengers in 2019) within 7 to 15 hours of travel times.



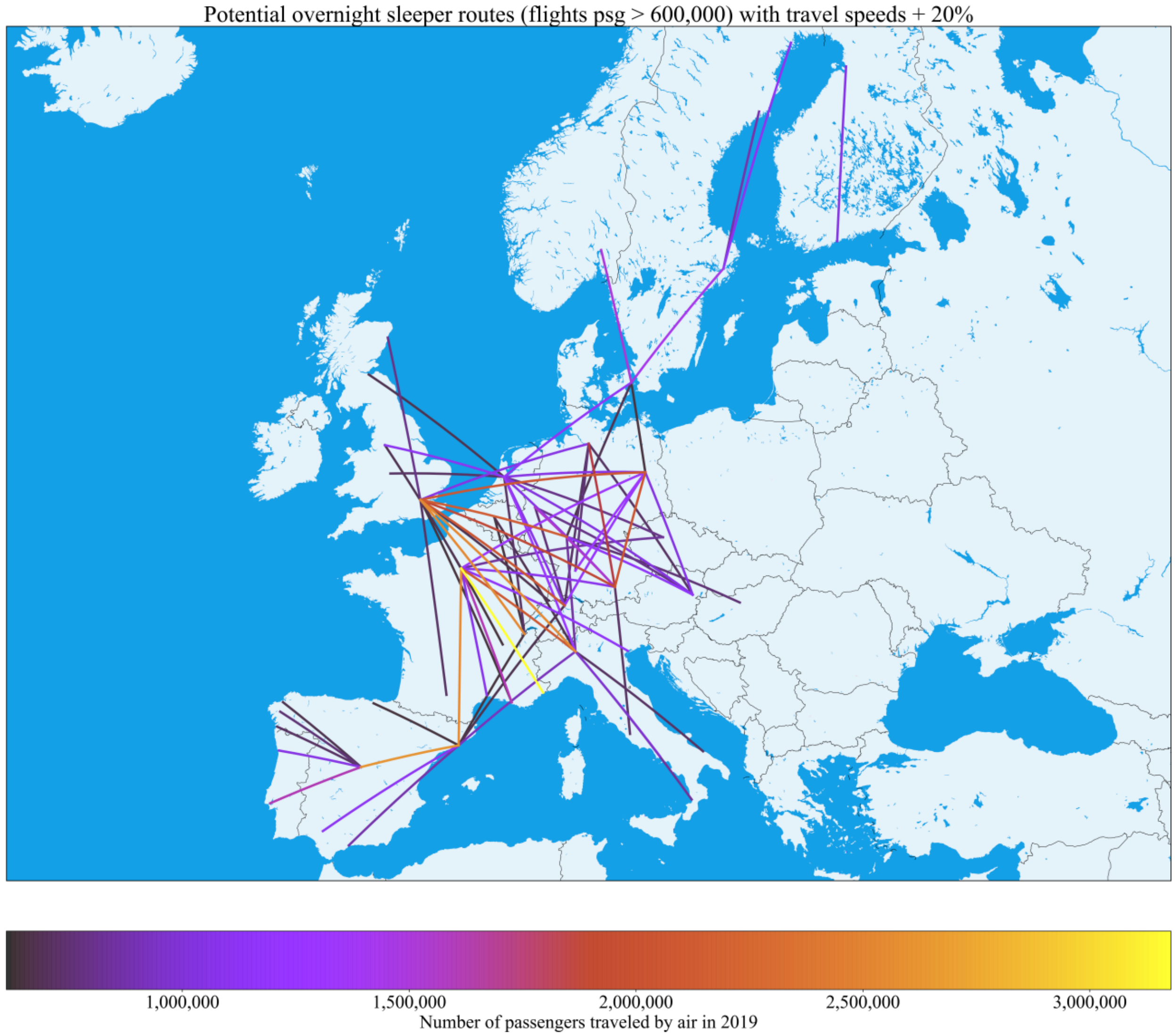
Appendix Figure 12 Filtered routes with travel speeds reduced by 60%.



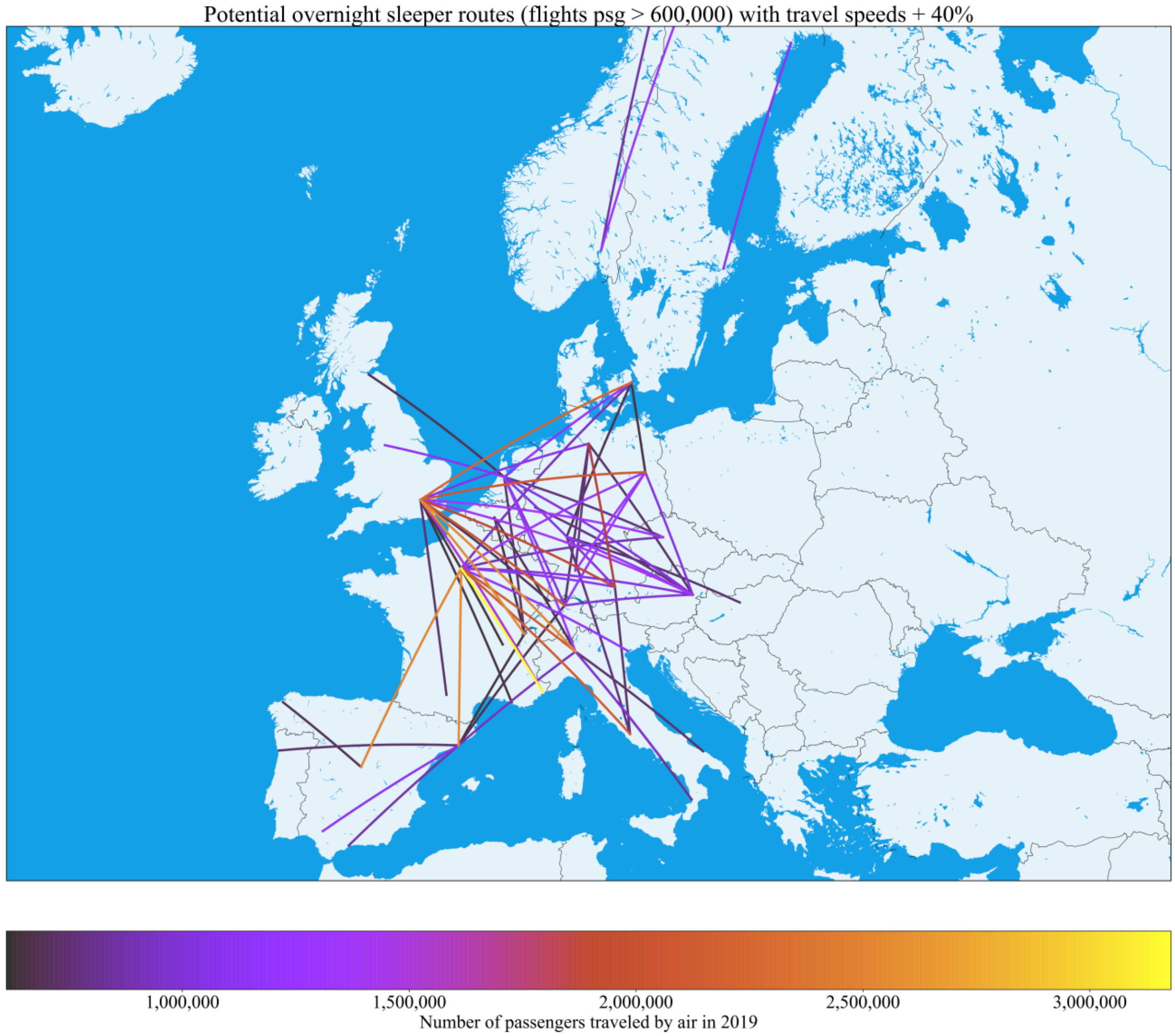
Appendix Figure 13 Filtered routes with travel speeds reduced by 40%.



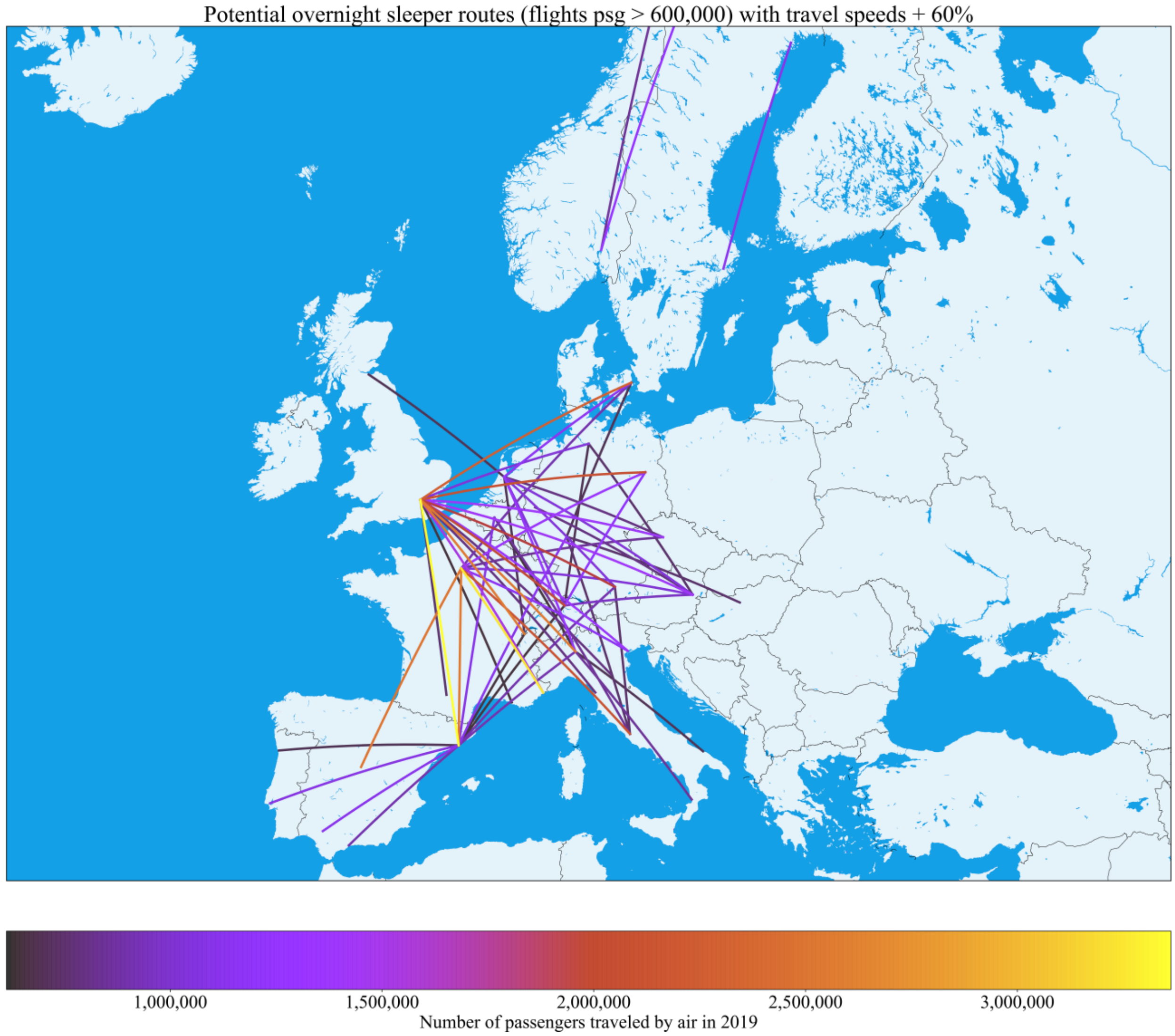
Appendix Figure 14 Filtered routes with travel speeds reduced by 20%.



Appendix Figure 15 Filtered routes with travel speeds increased by 20%.



Appendix Figure 16 Filtered routes with travel speeds increased by 40%.



Appendix Figure 17 Filtered routes with travel speeds increased by 60%.

Appendix – Tables

Routes	Great circle distance (km)	Min. flight time (h)	Min. railway time (h)	Ratio (railway/flight)
Hamburg-Zurich	695	1.5	7.5	5.0
Barcelona-Paris[i]	830	1.9	8.3	4.4
Rome-Zurich[ii]	683	1.6	7.7	4.8
Vienna-Stuttgart	592	1.3	7	5.4
Amsterdam-Lyon[iii]	734	1.6	5.8	3.6
London-Glasgow	556	1.3	5.2	4.0
Warsaw-Riga	561	1.3	11.8	9.1
Oslo-Stockholm	416	0.9	6.7	7.4

Appendix Table 1 A selection of routes in Europe with the comparison of travel time in air versus railway on the same day, derived from [55, 109, 110]. Great-circle distance is the shortest distance between any two points on the surface of a sphere that is measured along a path on the surface of the sphere.

Trademark/train name	Operator	Start	End	Duration (h)	Distance (km)	Speed (km/h)
Berlin Night Express	Snälltåget	Berlin	Malmö	10	833.6	83.4
EuroNight	PKP	Prague	Warsaw	9	748.5	83.2
EuroNight	MAV	Budapest	Bucharest	17	841	49.5
EuroNight	HŽ	Zagreb	Munich	8.8	583.1	66.3
EuroNight	HŽ	Zagreb	Zurich	14.6	907.5	62.2
EuroNight	HŽ	Rijeka	Munich	10.2	764.9	75.0
EuroNight	MAV	Budapest	Munich	9.5	692.8	72.9
EuroNight	MAV	Budapest	Zurich	11.6	1017.3	87.7
EuroNight	MAV	Budapest	Berlin	14.5	1014	69.9
EuroNight	ČD	Prague	Zurich	13.4	802	59.9
EuroNight	PKP	Vienna	Warsaw	11.3	691	61.2
Hellas Express	Srbija Voz	Thessaloniki	Belgrade	15.5	683.7	44.1
Intercités de Nuit	SNCF	Paris	Latour de Carol	11	1009.2	91.7
Intercités de Nuit	SNCF	Paris	Rodez	7.1	694.5	97.8
Intercités de Nuit	SNCF	Paris	Briançon	11.6	814	70.2
Intercités de Nuit	SNCF	Paris	Portbou	12.6	1122.8	89.1
Santa Claus Express	V.R.	Helsinki	Rovaniemi	12.8	918	71.7
Santa Claus Express	V.R.	Helsinki	Kemijärvi	14.2	893	62.9
Santa Claus Express	V.R.	Tampere	Rovaniemi	9	711	79.0
SJ Night train	SJ	Gothenburg	Östersund	13	923	71.0
SJ Night train	SJ	Gothenburg	Luleå	16.5	1250	75.8

[i] Perpignan-Paris is carried by high-speed rail.
[ii] Rome-Milan is carried by high-speed rail.
[iii] Brussels-Lyon is carried by high-speed rail.

SJ Night train	SJ	Stockholm	Östersund	9	538.3	59.8
SJ Night train	SJ	Stockholm	Luleå	12.5	1184.4	94.8
SJ Night train	SJ	Malmö	Stockholm	7.5	614	81.9
Snälltåget	Snälltåget	Malmö	Åre	16	1257	78.6
Thello	Thello	Paris	Venice	14.3	1135	79.4
Trenhotel	renfe	Madrid	Lisbon	9.8	805.8	82.2
Trenhotel	renfe	Hendaye	Lisbon	13	1081.9	83.2
Trenhotel	renfe	Barcelona	A Coruña	14.9	1258.3	84.4
Trenhotel	renfe	Barcelona	Vigo	15.3	1240	81.0
Trenhotel	renfe	Madrid	Ferrol	13	667	51.3
Trenhotel	renfe	Madrid	Pontevedra	11.3	667	59.0
Intercity Notte	Trenitalia	Rome	Siracusa	12.3	859	69.8
Intercity Notte	Trenitalia	Milan	Lecce	12.8	1032	80.6
Intercity Notte	Trenitalia	Rome	Lecce	7.6	669	88.0
Intercity Notte	Trenitalia	Turin	Lecce	13	1155	88.8
Intercity Notte	Trenitalia	Milan	Palermo	20.8	1468	70.6
Intercity Notte	Trenitalia	Rome	Palermo	12.4	921	74.3
Intercity Notte	Trenitalia	Turin	Reggio di Calabria	19	1357	71.4
Intercity Notte	Trenitalia	Turin	Salerno	12.6	985	78.2
Intercity Notte	Trenitalia	Milan	Siracusa	21.2	1409	66.5
Intercity Notte	Trenitalia	Rome	Trieste	10.8	804.3	74.5
The Highland Caledonian Sleeper (CAL)	Caledonian Sleeper	Inverness	London	11	1010.0	91.8
The Highland Caledonian Sleeper (CAL)	Caledonian Sleeper	Aberdeen	London	10.4	953.8	91.7
The Lowland Caledonian Sleeper (CAL)	Caledonian Sleeper	Glasgow	London	7.5	741.3	98.8
The Lowland Caledonian Sleeper (CAL)	Caledonian Sleeper	Edinburgh	London	7.5	743.4	99.1
The Deerstalker (CAL)	Caledonian Sleeper	Fort William	London	12	934.8	77.9
The Night Riviera (RIV)	BritRail	Penzance	London	7.7	620.9	80.6
ÖBB Nightjet	ÖBB	Vienna	Bregenz	9.5	626	65.9
EuroNight	ÖBB	Villach	Feldkirch	8.5	529.6	62.3
ÖBB Nightjet	ÖBB	Graz	Feldkirch	8.9	701.5	78.8
ÖBB Nightjet	ÖBB	Vienna	Zurich	10.9	749	68.7
ÖBB Nightjet	ÖBB	Graz	Zurich	10.9	888	81.5
ÖBB Nightjet	ÖBB	Hamburg	Zurich	12.2	929.4	76.2
ÖBB Nightjet	ÖBB	Berlin	Zurich	12.1	990	81.8
ÖBB Nightjet	ÖBB	Vienna	Berlin	11.8	976.3	82.7
ÖBB Nightjet	ÖBB	Vienna	Brussels	14.3	1213.3	84.8
ÖBB Nightjet	ÖBB	Vienna	Hamburg	12.4	1140.8	92.0
ÖBB Nightjet	ÖBB	Vienna	Düsseldorf	12	1025.1	85.4
ÖBB Nightjet	ÖBB	Innsbruck	Brussels	14.3	1019.3	71.3

ÖBB Nightjet	ÖBB	Innsbruck	Düsseldorf	12	790.7	65.9
ÖBB Nightjet	ÖBB	Innsbruck	Hamburg	12.3	993	80.7
ÖBB Nightjet	ÖBB	Vienna	Rome	14	1116.7	79.8
ÖBB Nightjet	ÖBB	Vienna	Milan	12.8	855	66.8
ÖBB Nightjet	ÖBB	Vienna	Venice	11	603.2	54.8
ÖBB Nightjet	ÖBB	Vienna	Livorno	12.5	925.7	74.1
ÖBB Nightjet	ÖBB	Munich	Rome	13.2	920.8	69.8
ÖBB Nightjet	ÖBB	Munich	Milan	12	541	45.1
ÖBB Nightjet	ÖBB	Munich	Venice	9.3	559	60.1

Appendix Table 2 Available night train routes in Europe, derived from [51, 52, 54, 57]. This study assumes that the departing night trains each night are normally bi-directional, indicating that the total number of trains will be doubled as the number of night trains showing above.

routes (city-city)	bi-direction psg departed (2019)	domestic flight	distance (km)	railway distance (km)	mean railway speed (km/h)	railway travel time (h)
BARI-MILANO	703,024	TRUE	787.50	860.67	73.96	11.64
WIEN-DUESSELDORF	770,693	FALSE	781.46	866.74	72.04	12.03
BERLIN-DUESSELDORF	1,233,050	TRUE	477.41	537.60	73.08	7.36
AMSTERDAM-BERLIN	1,002,022	FALSE	575.82	652.15	73.12	8.92
PARIS-MARSEILLE	1,558,924	TRUE	663.60	752.40	86.03	8.75
NAPOLI-MILANO	902,309	TRUE	656.01	765.87	73.96	10.36
KOELN-BERLIN	1,434,719	TRUE	478.63	560.89	73.08	7.68
ROMA-MILANO	1,192,843	TRUE	477.33	565.68	73.96	7.65
MALMO-STOCKHOLM	1,023,098	TRUE	517.18	622.79	77.42	8.04
TOULOUSE-PARIS	3,216,294	TRUE	587.99	719.08	86.03	8.36
LONDON-EDINBURGH	3,374,774	TRUE	535.55	658.86	90.00	7.32
LONDON-FRANKFURT	2,067,200	FALSE	637.45	784.32	81.54	9.62
LYON-LONDON	623,617	FALSE	733.97	904.61	88.02	10.28
OULU-HELSINKI	956,926	TRUE	537.74	664.83	71.20	9.34
WIEN-FRANKFURT	1,108,897	FALSE	608.89	753.02	72.04	10.45
PARIS-MONTPELLIER	989,305	TRUE	596.93	741.33	86.03	8.62
PARIS-FRANKFURT	1,041,037	FALSE	478.57	594.99	79.55	7.48
MUENCHEN-AMSTERDAM	969,878	FALSE	666.88	829.60	73.12	11.35
PARIS-ZURICH	723,610	FALSE	490.53	617.18	80.01	7.71
STOCKHOLM-KOBENHAVN	1,387,160	FALSE	525.54	662.97	75.29	8.81
PARIS-MUENCHEN	1,014,022	FALSE	686.19	869.80	79.55	10.93
BERLIN-FRANKFURT	2,248,716	TRUE	425.11	539.79	73.08	7.39

PARIS-MANCHESTER	683,651	FALSE	606.56	773.26	88.02	8.79
KOELN-MUENCHEN	1,017,011	TRUE	456.81	583.95	73.08	7.99
SANTIAGO-MADRID	719,748	TRUE	489.46	626.57	70.28	8.91
ROMA-MUENCHEN	717,631	FALSE	697.61	894.76	73.52	12.17
MUENCHEN-HAMBURG	1,740,129	TRUE	613.39	786.87	73.08	10.77
ZURICH-LONDON	1,946,968	FALSE	776.27	997.94	81.99	12.17
LONDON-DUESSELDORF	1,008,254	FALSE	480.22	618.96	81.54	7.59
DUESSELDORF-MUENCHEN	1,488,008	TRUE	487.32	630.17	73.08	8.62
BASEL-LONDON	653,795	FALSE	706.69	917.09	81.99	11.18
LONDON-GLASGOW	2,285,771	TRUE	557.79	726.52	90.00	8.07
LONDON-GENEVA	2,509,955	FALSE	745.61	973.19	81.99	11.87
MUENCHEN-BERLIN	1,933,810	TRUE	505.80	661.37	73.08	9.05
HAMBURG-FRANKFURT	1,426,018	TRUE	394.70	520.68	73.08	7.13
MADRID-BARCELONA	2,572,893	TRUE	505.58	672.52	70.28	9.57
FRANKFURT-MILANO	813,757	FALSE	516.92	689.82	73.52	9.38
HAMBURG-ZURICH	692,724	FALSE	694.44	929.52	73.53	12.64
HAMBURG-LONDON	977,778	FALSE	721.44	967.15	81.54	11.86
LONDON-ABERDEEN	772,127	TRUE	643.88	866.50	90.00	9.63
ZURICH-AMSTERDAM	976,448	FALSE	611.41	826.14	73.57	11.23
STUTTGART-HAMBURG	736,612	TRUE	533.91	723.12	73.08	9.90
MILANO-PARIS	2,036,432	FALSE	642.57	871.00	79.99	10.89
BRUSSELS-MILANO	652,811	FALSE	697.75	946.17	76.01	12.45
GENEVA-BARCELONA	640,835	FALSE	624.11	850.90	72.13	11.80
ACORUNA-MADRID	680,075	TRUE	505.63	692.18	70.28	9.85
OSLO-STOCKHOLM	1,386,340	FALSE	418.01	574.15	75.29	7.63
KOBENHAVN-OSLO	1,467,630	FALSE	483.84	668.45	73.16	9.14
UMEA-STOCKHOLM	860,572	TRUE	511.30	708.79	77.42	9.16
ZURICH-DUESSELDORF	747,857	FALSE	446.36	626.71	73.53	8.52
BERLIN-ZURICH	1,164,277	FALSE	669.26	948.63	73.53	12.90
NICE-PARIS	3,178,806	TRUE	687.26	974.29	86.03	11.33
TRONDHEIM-OSLO	2,103,647	TRUE	390.01	556.42	73.16	7.61
VIGO-MADRID	683,930	TRUE	467.99	668.28	70.28	9.51
STUTTGART-BERLIN	1,234,360	TRUE	511.12	742.23	73.08	10.16
BILBAO-BARCELONA	622,601	TRUE	469.29	685.86	70.28	9.76

MADRID-LISBOA	1,558,588	FALSE	504.42	742.52	76.50	9.71
BRUSSELS-GENEVA	612,419	FALSE	531.58	805.11	76.02	10.59
BILBAO-MADRID	835,758	TRUE	323.35	504.17	70.28	7.17
MADRID-PORTO	969,958	FALSE	424.38	674.99	76.50	8.82
AMSTERDAM-LONDON	4,723,472	FALSE	358.17	572.37	81.58	7.02
AMSTERDAM-BIRMINGHAM	702,870	FALSE	464.25	758.84	81.58	9.30
AMSTERDAM-MANCHESTER	1,067,164	FALSE	497.33	867.17	81.58	10.63
KOBENHAVN-BERLIN	626,152	FALSE	355.64	797.84	73.12	10.91

Appendix Table 3 Potential overnight sleeper routes with passenger volume > 600,000 in 2019 and adequate distance and travel times for railway transport to operate.

Country	**CI of gross electricity production (combustion only) [g/kWh]**	**CI of gross electricity production (with upstream) [g/kWh]**	**CI of net electricity production (with upstream emissions) [g/kWh]**	**CI of electricity traded (with upstream) [g/kWh]**	**CI of electricity supplied (with upstream) [g/kWh]**	**Variation of CI after trade [%]**	**CI of electricity consumed at HV (with upstream) [g/kWh]**	**CI of electricity consumed at MV (with upstream) [g/kWh]**	**CI of electricity consumed at LV (combustion only) [g/kWh]**	**CI of electricity consumed at LV (with upstream) [g/kWh]**
Austria	133	151	156	170	315	85%	322	325	305	334
Belgium	188	224	233	239	257	8%	261	262	224	267
Bulgaria	507	532	585	601	589	-2%	618	628	636	669
Croatia	231	273	282	285	465	63%	487	494	463	524
Cyprus	646	737	773	773	773	0%	787	792	710	810
Czech Republic	518	545	587	596	640	7%	657	663	643	685
Denmark	316	368	386	386	356	-8%	364	367	328	377
Estonia	1020	1022	1152	1152	840	-27%	878	891	931	944
Finland	171	200	209	209	204	- 2%	207	207	181	211
France	66	88	92	93	97	4%	100	101	80	105
Germany	485	534	567	574	588	2%	599	602	558	615
Greece	655	695	755	757	712	-6%	732	739	723	767
Hungary	310	340	368	368	369	0%	383	388	365	407
Ireland	459	533	555	568	570	0%	588	594	530	617
Italy	358	427	444	448	402	-10%	413	417	362	431
Latvia	134	173	185	185	1075	482%	1110	1122	1140	1168
Lithuania	204	246	262	315	358	14%	370	374	331	390
Luxembourg	236	283	283	585	505	-14%	508	509	467	513
Malta	731	831	868	868	910	5%	954	970	908	1032
Netherlands	479	559	582	582	547	-6%	555	558	494	569
Poland	770	847	929	934	911	-3%	937	946	890	980

Portugal	295	346	355	365	357	-2%	372	378	340	400
Romania	356	379	413	416	425	2%	449	457	460	492
Slovakia	173	199	211	215	407	90%	412	414	383	420
Slovenia	315	329	351	361	302	-16%	309	312	291	321
Spain	248	295	305	312	309	1%	321	325	287	341
Sweden	16	24	25	25	44	74%	45	46	36	47
United Kingdom	469	555	584	591	576	-3%	593	599	526	623
EU 28 average	***340***	***387***	***407***	***413***	***417***	***1%***	***428***	***432***	***393***	***447***

Appendix Table 4 Carbon intensities of electricity for 28 Member States of the E.U. as of 2013 [103].

Appendix – Pseudocodes

```
# each row includes origins' latitudes and longitudes, destinations' latitudes and longitudes, and the
# number of passengers
set data = import CSV files

set psgMax = the highest number of passengers
set psgMin = the lowest number of passengers
set mapColormap = map's colormap

set Basemap latitudes, longitudes, projections
set Basemap background color, coastline color, lake color, boundaries

# to match colormap's gradient, normalization is necessary
set norm = normalize data with psgMin and psgMax

for eachRow in norm
    define color of eachRow based on mapColormap
    set great circle line for eachRow

set legend with max = psgMax, min = psgMin
set legendColormap where mapColormap's gradient = legendColormap's gradient

plot Basemap with great circle line and legend
save Basemap
```

Pseudocode 1 Procedures to visualize flight routes. It should be noted that the pseudocode includes the two colormaps, which the map's colormap is for plotting the routes and the legend's colormap is for plotting the legend, and the gradients are identical for two colormaps. I do so because the Python toolkit that I use does not support colormap legend for line plots.

```
# each row of data includes latitude, longitude, and the number of passengers
set data = import CSV files

set colormap

set Basemap latitudes, longitudes, projections
set Basemap background color, coastline color, lake color, boundaries

for eachRow in data
    define color of eachRow by the number of passengers based on colormap
    set scatter for eachRow

# Toolkit supports legend in scatter plot.
plot Basemap with scatters with legend
save Basemap
```

Pseudocode 2 Procedures to visualize scatter map.

```
set data = import CSV files
```

```
add column "railway distance" to store railway distance of flight route to data

for eachRow in data
    set urlPage with geolocations
    open webdriver
    use webdriver to get urlPage
    get elements by full xpath
    add distance to data["railway distance"]
    close webdriver

save data
```

Pseudocode 3 Procedures to automatically retrieve railway distance for flight route.

Appendix – Descriptions of analysis

This method is based on various reports with some assumptions [1-3, 12, 17, 18]. The estimation started with the results that 1,313 Mt of CO_2 was produced by the entire transportation sector as presented in Figure 1-3: 13.9% of CO_2 emissions were attributed to air transport; hence, total CO_2 emissions from air transport were 182.5 Mt in 2017. Citing the result that 1,116 billion passenger-kilometers were through air transport, I can derive a very rough calculation of CO_2 emissions per passenger-kilometers. With the assumption presented above, I derive that CO_2 emission per passenger-kilometers from air transport equals to $E_{EU-air-ppk-1} = \frac{1313\ Mt \cdot 13.9\%}{1{,}116\ billion\ passenger\ kilometers} = 163$ gCO_2 per passenger-kilometer.

Method Description 1 Estimation method 1 for air transport's carbon emissions per passenger-kilometer.

This method is a calculation and assumption-based method based on various reports [1-3, 5, 15]. By making the assumption that 4.3 billion passengers transported by air evenly shared 895 million tons of CO_2 generated and citing Eurostat's number of passengers traveled in 2018 intra-EU28, 64% of 1.181 billion passengers, I estimate that $E_{EU-air-2} = \frac{1.181\text{ billion passengers}\cdot 64\%}{4.3\ billion\ passengers} \cdot 895\ Mt = 153.49$ million tons of CO_2 were generated by E.U. flights (including E.U. national flights and intra-EU international flights), giving 157,320 gCO_2 generated per passenger [1, 5, 15]. Applying another estimation of average traveling distance of 1,070 kilometers per passenger by air, I derive that $E_{EU-air-pkk-2} = \frac{157{,}320\ g\ per\ passenger}{1{,}070\ kilometers} = 147$ gCO_2 per passenger-kilometer [1-3]. As the source does not specify whether the global CO_2 emissions include freights, the deficiency of such a calculation is that it may not distinguish whether the amount of CO_2 was generated by freight or passenger flights.

Method Description 2 Estimation method 2 for air transport's carbon emissions per passenger-kilometer.

This method cites sources from Eurostat's number of passengers traveled in 2018, 1,106 million passengers, Eurostat's number of CO_2-equivalent emissions in 2018, 182.45 million tons, and each passenger's average traveling distance in air transport by approximations, 1,070 kilometers [1-3, 20]. From these sources, I derive that $E_{EU-air-pkk-3} = \frac{182.45\ Mt}{1{,}070\ kilometers \cdot 1{,}106\ million\ passenger} = 154$ gCO_2 per passenger-kilometer. This method uses the least amount of assumptions compared to the previous two methods.

Method Description 3 Estimation method 3 for air transport's carbon emissions per passenger-kilometer.

The derivation of CO_2 emissions of railway transportation is shown as $E_{EU-rail-ppk-1} = \frac{1313\ Mt \cdot 0.5\%}{484.79\ billion\ passenger\ kilometers} = 13.5$ gCO_2 per passenger-kilometer in 2017, by using the same assumptions as presented in Method Description 1 and Figure 1-2 [6, 12].

Method Description 4 Estimation method 1 for railway transport's carbon emissions per passenger-kilometer.

The first step is to separate each entry into an origin airport and destination airport. With Excel's function *Text to Columns*, I split the *"AIRP_PR/TIME"* into two variables, *"origin airport"* and *"destination airport"*. As shown in Table 2-1, the hyphen works for two purposes. Firstly, the hyphen is the connector for each route. Also, in some cases, it is an element of names of the origin or the destination. For instance, route *"BELFAST/ALDERGROVE airport - PARIS - CHARLES DE GAULLE airport"* can be found with two hyphens. The methodology that I applied here is to filter out cells with more than two hyphens and find the exceptions in which the name of the airport also includes hyphens. I found several cases, such as Vienna Schwechat Airport, Paris Charles de Gaulle Airport, and Berlin Tegel Airport. I manually split the origin and destination airport for such instances.

As this study aims to find the replaceability of current flight routes with overnight sleepers, I care more about city connections than the actual flight routes. Hence, the second step is to filter out the origin and destination cities of each route. Usually, the names of cities appear at the beginning of the official names of the airports. For exceptional cases, such as Adolfo Suárez Madrid–Barajas Airport of Madrid, Spain, I allocated the belonging cities manually in Excel.

The third step is to create a new variable in the Excel naming *"routes (city-city)"* to store the flight routes in a "City A-City B" form.

The second last step of processing is introducing another variable naming *"conjugate psg departure"*. The purpose of introducing such a variable is to consolidate the data further because inbound and outbound routes are two separate entries in the dataset. The new variable's introduction allows storing data for the total number of passengers from both inbound and outbound flights of a particular flight route. As 35 datasets were aggregated into one set, for each route operating internationally within 35 countries or domestically, I should be able to find a conjugate pair for the reverse direction. I consolidated the data, shown as Description Table 1. *"EU-flight"* was derived when the number of conjugate passengers departed is non-zero, based on the assumption that non-EU flight does not have a conjugate pair in the dataset. Admittedly, exceptions were found, such as Czechia's outbound flight did not record specific destination airports but only destination countries. For such exceptions, manual adjustments were also applied.

Routes (city-city)	**psg departed (2019)**	**conjugate psg departed (2019)**	**EU-flight**
DUBLIN-LONDON	2,480,989	2,471,652	TRUE
LONDON-DUBLIN	2,471,652	2,480,989	TRUE
…	…	…	…
LONDON-ATLANTA	300,009	-	FALSE

Description Table 1 Sample of consolidated data of Eurostat's passenger statistics based on routes."EU-flight" indicates whether the flight route has both the origin and destination within 35 countries, which Eurostat has data.

Finally, I consolidated the mutually conjugating routes, like Dublin-London and London-Dublin routes, and extracted the intra-Europe and domestic flight. The sample data is shown in Description Table 2.

routes (city-city)	**psg departed (2019)**	**conjugate psg departed (2019)**	**bidirectional psg departed (2019)**
DUBLIN-LONDON	2,480,989	2,471,652	4,952,641
AMSTERDAM-LONDON	2,403,880	2,319,592	4,723,472
…	…	…	…

Description Table 2 Sample of consolidated Eurostat's passenger data with outbound, inbound, and total passengers in descending order.

Method Description 5 Description of data processing procedures for Eurostat's flight passenger data.

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