MSc Thesis

Modeling and analyzing the environmental impact of short-to-medium range air and ground transports

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TUDelft

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Modeling and analyzing the environmental impact of short-to-medium range air and ground transports

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Preface

I started this master's thesis in October 2022 as a part of my study progress to obtain the TU Delft master's degree in Aerospace Engineering. This research aims to provide transportation choice suggestions for travelers quantitatively by performing an environmental analysis of the existing air and ground transport system. I hope the results can contribute to both individual passenger travel choice, and also inspires the policy maker to promote sustainability development in Europe.

First and foremost, I would like to express my sincere appreciation to my supervisor Dr. Junzi, whose insights and guidance have significantly enriched my comprehension of the subject matter and helped me overcome challenges along the way. I also would like to express my thankfulness to Prof. dr. ir. Jacco Hoekstra, for his valuable feedback and instructions, which improves my work quality. With the support of both Dr. Junzi and Prof. Jacco Hoekstra, I have a great time working on my master's thesis.

In the end, I am always thankful to my family and friends who support me all the time. Thank them for their encouragement and warmth all the time.

Ying Chen
Delft, August 2023

Nomenclature

Abbreviations

Abbreviation	Definition
API	Application Programming Interface
BEV	Battery electricity vehicle
CO_2	Carbon Dioxide
$CO_{2,eq}$	Carbon Dioxide Equivalent
CH_4	Methane
N_2O	Nitrous oxide
GCR	Great circle distance
GHG	Greenhouse Gas
GTFS	General Transit Feed Specification
HEV	Hybrid electric vehicle
HSR	High speed Rail
LCA	Life Cycle Assessments
PHEV	Plug-in hybrid electric vehicle
TTW	Tank-to-wheel
WTT	Well-to-tank
WTW	Well-to-wheel

Symbols

Symbol	Definition	Unit
$d_{A,B}$	Great circle distance	[km]
f_b	Fuel burn	[kg]
h_v	heat value	[MJ/kg]
km	Kilometer	[km]
kg	Kilogram	[kg]
pkm	Pasengerkilometer	[pkm]
LCA	Life-cycle emissions	$[kgCO_{2,eq}]$
WTW	Well-to-wheel emissions	$[kgCO_{2,eq}]$
ϕ	Longitude	[deg]
λ	Latitude	[deg]
V	Velocity	[m/s]

I Scientific Paper

Modeling and analyzing the environmental impact of short-to-medium range air and ground transports

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The emissions of the transport sector inside the EU-27 have risen by 33 % between 1990 and 2019. A modal shift from unsustainable transport towards more environmentally friendly transport modes can be taken as one solution to mitigate the overall emission of the transport sector. In this paper, multiple open-source models and databases are utilized to compare travel emissions and time of air travel and various ground transport options, including car, bus, and rail. Compared with previous research that relies on closed-sourced or hand-collected data to extract public ground transportation routes information, this paper utilizes the openly accessible General Transit Feed Specification(GTFS) database, facilitating the calculation at a large scale inside EU-27. 820 pairs of routes between popular 41 city centers inside EU-27 are selected for comparison. The results consistently demonstrate that air travel always produces higher emissions per passenger than rail and bus travel for all routes. Emissions from cars are significantly influenced by occupancy rates and the type of vehicle fuel. The emissions from a single person in a petrol/diesel car can exceed those from air travel. However, if four people travel in a hybrid electric or electric vehicle, the per-passenger emission can be similar to rail. Among all public transport, the rail is the most competitive one to replace air travel by offering passengers similar travel time and reducing emissions. The trade-off factor between emissions and time is also investigated on its effect on the passenger route choice decision. In addition, this paper offers insights into the development of emission models and provides recommendations for various stakeholders.

Keywords: modal shift, sustainability, transportation, General Transit Feed Specification(GTFS), emission

I. Introduction

The European Green Deal includes the objective of achieving a 90% reduction in transport-related greenhouse gas(GHG) emissions by 2050. However, between 1990 and 2019, the emissions of transport inside EU-27 have risen by 33%, even as other sectors have reduced emissions by 34% [1]. In 2019, the transport sector accounted for 26% of total greenhouse gas emissions in EU-27 [2].In order to reach the European Green Deal goal, it is important to develop approaches to reduce transportation emissions. Research has shown that one way to reduce overall transportation emissions could be through a modal shift to choose a more environmental-friendly transportation method on a certain route. When looking at emissions of the different transportation types, current aviation operations rely heavily on fossil fuels. It remains one of the least energy-efficient transportation methods nowadays, and aviation emission is forecast to have the largest increases up to 2030. Compared with aircraft, ground transport is rapidly adopting more sustainable energy sources. The road sector's emission is expected to decrease to around 67% as the percentage of petrol /diesel cars will continue to decrease in the following years. Rail is the most energy-efficient mode of passenger transport nowadays. Train travel only accounts for less than 1% of total transportation emissions and is expected not to increase in the future 30 years[2].

Considering the high energy efficiency of rail transportation, the replacement of short-haul flights with high-speed rail (HSR) has been widely discussed as a viable solution to reduce travel emissions while maintaining comparable travel times for passengers [3]. However, the current network by HSR in EU-27 is very limited there are around 96% percent lengths of routes in Europe where the HSR is not equipped. The previous research has overlooked the role of long-distance coaches and cars, as well as non-high-speed rail (NHSR) trains. This paper aims to address this gap by discussing the potential range of replacement options and emission performance for various travel methods, including both high-speed rail (HSR) and NHSR rail, as well as buses and cars.

The previous research often uses closed-source or hand-collected datasets to find travel information, causing the results difficult to reproduce and conducting large-scale calculations challenging. This paper will solve this problem by building on a completely open database and model. The OPENAP model is used to calculate air travel emissions. The public ground transportation model is programmed based on the General Transit Feed Specification(GTFS) database to provide travel information. The GTFS database is a collection of txt files containing abundant travel information on railway trips, stops, departure/arrival time, train types, and company names, provided by each operator or country. The users can freely download the up-to-date GTFS and easily modify and compile the parameters in the GTFS file. It enables abundant research on the public ground transportation route.

Furthermore, most of the previous research [4] focuses only on the direct emission from fuel burn. The manufacture, and maintenance emission of vehicle and infrastructure is not fully discussed. This paper compares emissions both on the well-to-wheel (WTW) and life cycle analysis (LCA) levels. To provide a definition, well-to-wheel (WTW) emissions represent the emissions during the vehicle's operational phase. It is the add-up of both well-to-tank (WTT) and tank-to-wheel (TTW) emissions. Well-to-tank (WTT) emissions take place during the production, transmission, and distribution of the energy used by vehicles, while tank-to-wheel emissions (TTW) are related to the direct emission of fuel consumption during vehicle use. Compared with well-to-wheel (WTW) emissions, life cycle assessment (LCA) also considers energy and emissions involved in the construction and maintenance of the infrastructure and vehicle.

Overall, the objective of this research is to utilize multiple open-source models and databases to create a model for estimating and comparing the emissions, time, and frequency of various transportation modes, including aircraft, trains, buses, and cars. The outcome of this study will help passengers in selecting a more environmentally sustainable travel option without deteriorating their travel quality.

II. Methodology

This section presents the method for constructing the emission model for each transport type separately. Each emission model consists of two distinct components. The first component focuses on determining the travel route between the origin and destination points. Subsequently, the second component involves calculating emissions based on the determined travel route from the previous step. Additionally, the formula of potential emission saving related to the trade-off between travel emission and time is introduced.

A. Air transports model

Flight route data

This study utilizes Eurocontrol R&D data [5] to find the actual flight information. This database provides detailed flight data of all commercial flights across European that are registered on the EUROCONTROL network. It is noteworthy that during each year, only four months (March, June, September, and December) of data are provided in Eurocontrol R&D dataset. By querying the dataset using the International Civil Aviation Organization (ICAO) codes of the origin and destination airports, users can access detailed flight information such as the airlines, aircraft type code, actual routes flown, actual off-block time (departure time from the gate), actual arrival time, and so on. The in-flight travel time between the specified airports is determined by calculating the difference between the actual off-block time and the actual arrival time, with an additional 15 minutes incorporated to account for the taxi-in time after take-off. When evaluating the total travel time for passenger air transportation, it is important to consider various factors beyond the in-flight duration. These factors include check-in procedures, boarding time, baggage claim time after landing, and commuting time between cities and airports, all of which contribute to the overall air travel time. Considering all these factors, the additional time required for air travel, beyond the actual in-flight time, is estimated to be approximately 195 minutes.

For distance calculations, Eurocontrol provides the flight distance as the actual distance flown in nautical miles (nm) for each flight. The frequency of flights can also be determined by counting the occurrences between the specified origin and destination airports during a specified time period.

Air travel emission model

This study utilizes the open-source OpenAP Trajectory Optimizer[6] to compute the aircraft emission. The model generates optimized routes between the origin and destination, and the fuel flow model is constructed based on the publicly available ICAO aircraft engine emission databank [7]. The engine fuel flow under sea-level ambient conditions at four thrust settings representing different stages of flight is provided by ICAO. To estimate the fuel flow using OpenAP, three parameters are required: the aircraft type code (specifically the engine type), the flight distance, and the initial take-off mass. The aircraft type code and flight distance can be queried from the Eurocontrol database as described earlier. The default engine type is used for each aircraft type. However, the initial take-off mass needs to be determined by the user. Different take-off masses will introduce uncertainty to the results. To account for this uncertainty, three different take-off masses are defined: 70%, 80%, and 90% of the aircraft's maximum take-off weight. Figure 1 illustrates the result for aircraft A319 neo at different take-off mass settings that higher percentages of the maximum take-off weight result in

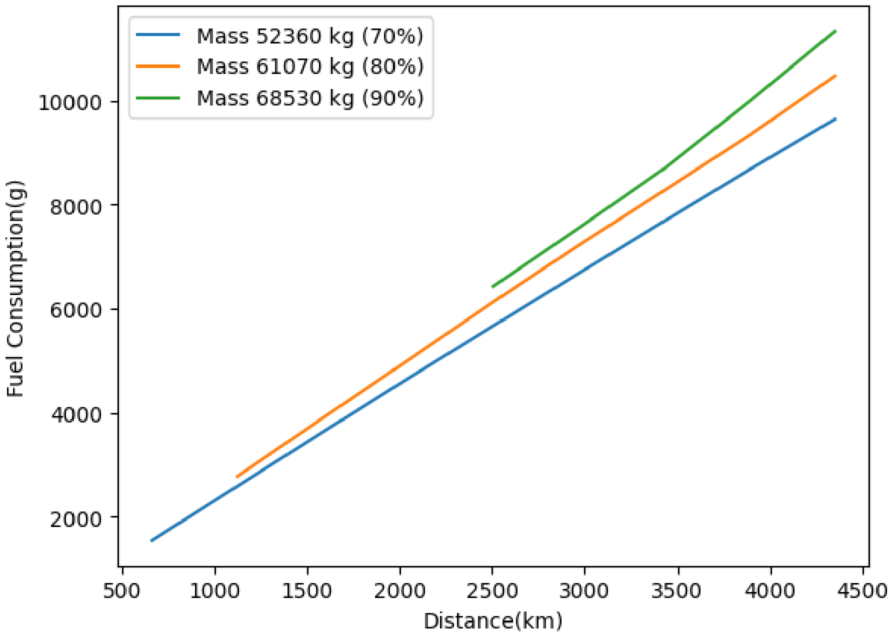


Figure 1. Fuel Consumption vs. Distance for take-off mass at 70%, 80% ,90% of Maximum take-off weight for aircraft A319 neo

a higher minimum possible flight distance. Furthermore, under the same distance, higher maximum take-off weights lead to higher emissions. Certain routes present invalid emission simulations due to the setting of too high take-off weights, leading it impossible to meet the maximum landing weight requirement. Consequently, the outcomes obtained from these specific cases are considered invalid and are, therefore, excluded from the analysis.

OpenAP currently defines aircraft performance and emission models for around 30 common aircraft-type and makes use of synonyms to approximate the models for an additional set of more than 20 less common aircraft types. These aircraft types are sufficient to cover the main aircraft types for intra-EU flights. The final formula is shown in Equation 1.

$$fb = \alpha_i \cdot d_g^2 + \beta_i \cdot d_g + \gamma_i \tag{1}$$

where fb is the fuel burn of a flight in kilograms. d_g is the actual flight distance between airport pairs driven from the Eurocontrol database.The α_i, β_i, γ_i are aircraft-type specific parameters driven by using ordinary least squares regression.

The Equation 2 shows how to transform fuel burn to the CO_2, CH_4, and N_2O emission per passenger.

$$\begin{aligned} CO_2 &= \frac{(fb \times 3.169) \times 1.9}{(ns \times lf)} \\ CH_4 &= \frac{(0.0000005 \times fb \times hv)}{(ns \times lf)} \\ N_2O &= \frac{(0.000002 \times fb \times hv)}{(ns \times lf)} \end{aligned} \tag{2}$$

where fb is fuel burn in kg driven from Equation 1. For CO_2 emission calculation, the fuel burn fb first multiplies with the emission factor- 3.169 kg/kg. In order to account for the non-CO2 effects of aviation, a factor of 1.9, as recommended by the Baumeister [8] was then applied to the CO_2 emissions. For calculating the CH_4 and N_2O emissions, 0.0005 g/MJ and 0.002 g/MJ were assumed. The assumed heat value of the fuel is 43 MJ/kg based on Baumeister [9]. n_s and l_f in the denominator represent the payload and occupancy. The average intra-EU occupancy rate is around 81.9% for 2018 from the IATA report [10].

The $CO_{2,eq}$ emissions per passenger is a method to convert amounts of other greenhouse gases(GHG) to the equivalent amount of CO_2. All transportation modes' $CO_{2,eq}$ were calculated based on IPCC's Fifth Assessment Report [11] by the following equation:

$$CO_{2,eq} = CO_2 + CH_4 \times 28 + N_2O \times 265 \tag{3}$$

The result from Equation 3 only considers the tank-to-wheel (TTW) emission of an aircraft as the direct emission from fuel combustion. The calculation method of the well-to-wheel (WTW) and life cycle asssessment(LCA) is followed in Equation 4:

$$\begin{aligned} WTW &= TTW(1 + P) \\ LCA &= WTW + AM \times x + A \times x \end{aligned} \tag{4}$$

where P is the well-to-tank (WTT) emissions factor that counts for the fuel production upstream emission of 0.538 $CO_{2,eq}$ kg/kg calculated by [12]. For the whole LCA emission calculation, AM represents aircraft manufacture, maintenance, and disposal emission factor of 0.0005 kg $CO_{2,eq}/pkm$, while A is the airport construction and maintenance, operation emissions of 0.0003 kg $CO_{2,eq}/pkm$ as estimated by [13]. Finally, x is the actual flight distance flown in kilometers.

B. Rail Model

Rail transportation model

In order to compute the emissions accurately, it is crucial to map out the travel route of rail first. There are already many APIs available to find the rail travel route between the origin/destination, like Google API. However, the majority of these APIs have a limit on the number of active sessions a user can have at any given time and are not free to access. This paper aims to build a completely open-source ground transportation route planning model based on the General Transit Feed Specification (GTFS) database. The GTFS database is an entirely open and free transport data specification published by public transit agencies. A GTFS feed is composed of a series of text files collected in a ZIP file. The link and information inside the GTFS files are defined in Figure 2.

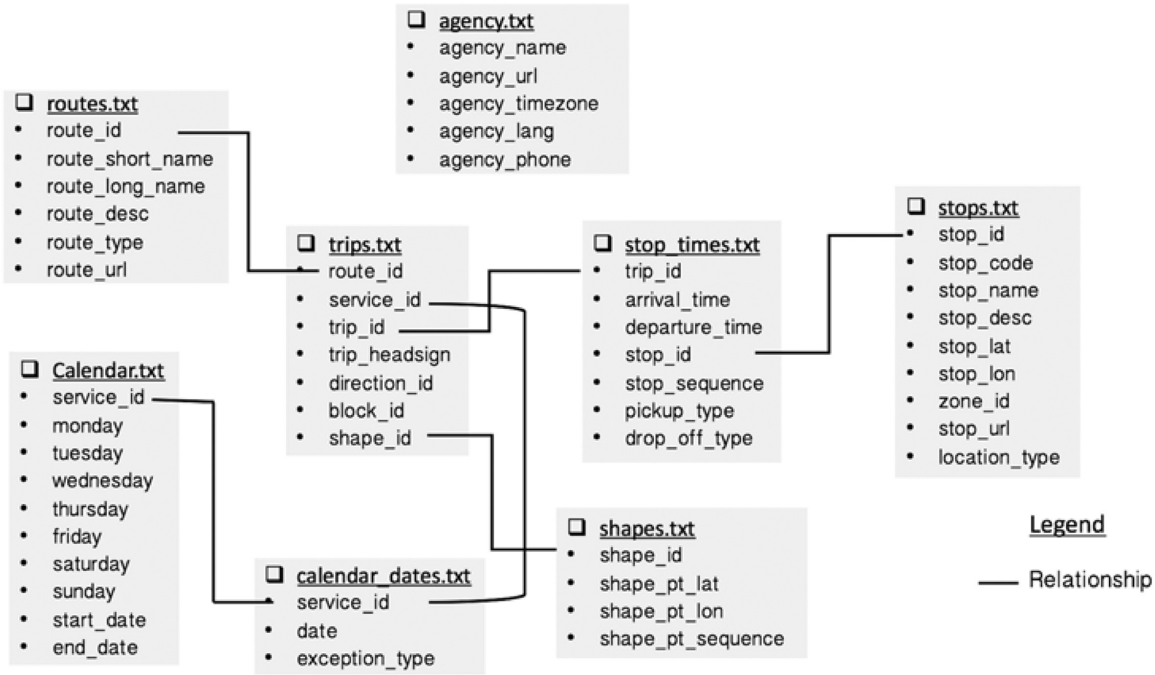


Figure 2. The GTFS link by [14]

Each file models a particular aspect of transit information: stops, routes, trips, and other schedule data. The explanation of five files in GTFS related to this study is defined in Table 1. To sum up, the calendar_txt and calendar_dates_txt files are employed to narrow down the dates when routes are operational. The stops_txt file assigns a unique stop_id to each stop and incorporates longitude and latitude information. The stop_times_txt file holds particular prominence in the constructed model as it identifies stops and captures arrival and departure timings along the route.

Table 1. The aspect of transit information from Google Transit[15]

file name	information
stops_txt	Identifies a stop, station with a unique stop_id, and contains the location of latitude and longitude for each stop
routes_txt	Identifies a route with a unique route_id. The agency for the specified route is specified by agency_id. This file also indicates the type of transportation used on a route (tram, bus, rail, subway, etc.)
stop_times_txt	Contains the stop_id and stop_sequence along each trip_id. One route_id has several corresponding trip_id, meaning operates on the same route but during different times and directions. Also, it has the arrival and departure time at each specific stop for a specific trip on a route.
calendar_txt	Use service_id to uniquely identify a set of dates when service is available for one or more routes.The service_id is connected with the route_id.
calendar_dates_txt	Indicates explicitly activate or disable service by date, use together with the *calendar_txt* to filter on the service active dates

The following Figure 3 shows the steps of using the origin and destination to calculate the route with no more than two transfers in GTFS.

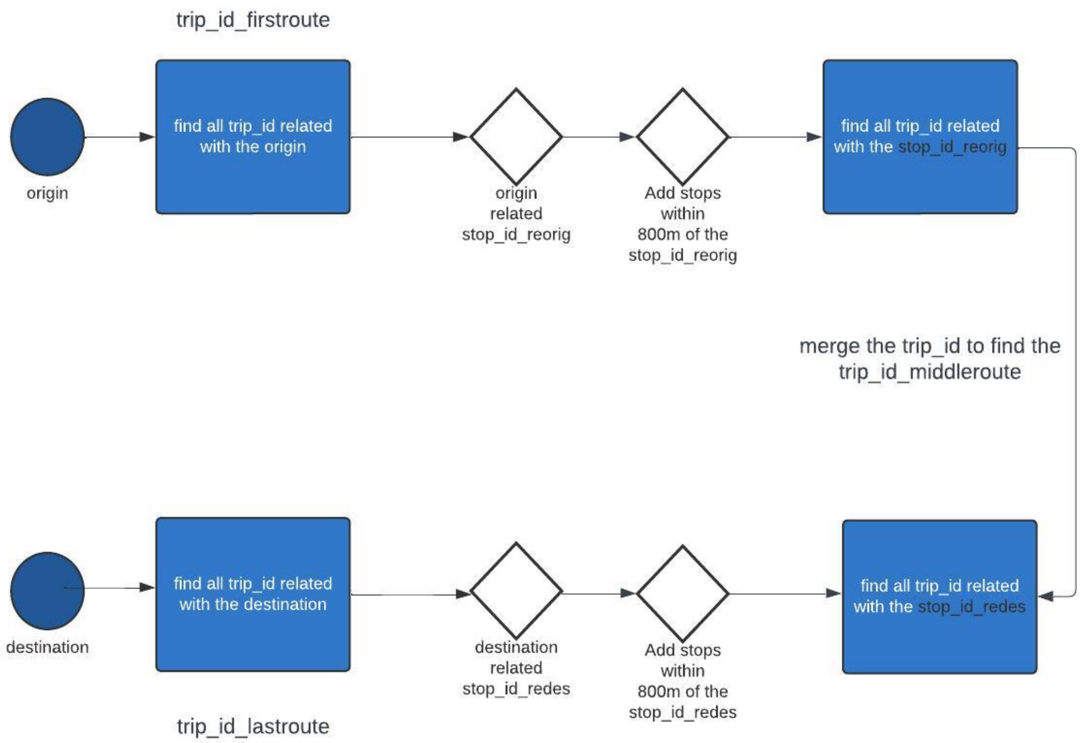


Figure 3. The GTFS method

The specific steps of searching the direct connection are depicted in Appendix A. To summarize, the first step is to identify all stops that can be reached from the origin or destination via trip_id in stop_times.txt. Next, we try to make pairs between these stops, which are identified that can be connected to each other through a trip. To ensure a realistic trip, the time must increase at each stop along the route, from origin to destination. The results of the model include the distance of each step of the trip, the travel time, the stops encountered along the trip, the types of trains used, the operator, and the frequency.

This research aims to gather GTFS by European operators. However, the GTFS from some operators are not publicly available. Figure 4 shows the availability of the GTFS for the countries in Europe. National-wide feeds covering almost all traffic information are available for Germany, France, Netherlands, Spain, and Belgium. The North European nations, including Sweden, Finland, and Norway, have complete GTFS data as well. However, in many countries in Eastern Europe, complete national wide GTFS data is unavailable. While data for Italy is also incomplete, it includes national-wide GTFS information from TRENITALIA, the country's largest operator. Portugal only has regional GTFS data available for a few cities. For these incomplete GTFS countries, which shows as the yellow and red color in Figure 4, the regional transportation information from operators is merged. And their main cross-border travel information is supplemented by Eurail [16], an all-in-one train ticket website with information on most trains across Europe.

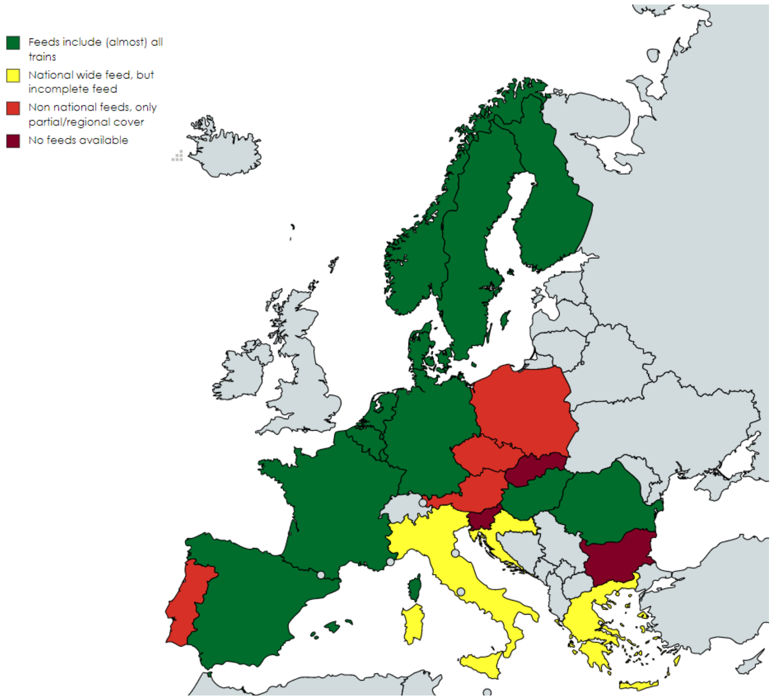


Figure 4. The rail GTFS availability inside EU-27

To notice that the GTFS nomenclature format is not uniform across Europe. Therefore, When merging GTFS from different countries or operators, they have their own defined stop_id and trip_id. Even at the same stop, different operators give different stop_id. At Table in Appendix A step 9, at the transfer point, all stop_id within 100m of the transfer stops are queried by using stop latitude and longitude information. This step enables finding the transfer trips provided by different operators/countries.

Rail emission model
Currently, in EU-27, the HSR train is almost all electric, while NHSR is around 80% electric. Therefore, this paper only considers the emission from electric-powered trains.The electric trains run solely on internal electric motors, resulting in no direct carbon emissions. However, their emissions originate from the electricity generation process, which primarily involves the burning of fossil fuels or coal at the well-to-train (WTT) stage. For electric rail, the method of calculating well-to-wheel(WTW) emission of the entire trip is shown in Equation 5

$$\text{Ei} = \sum_{i=\text{origin stop}}^{\text{destination stop}} \text{CI}_i \times \text{Distance}_i \times \text{EC}_i \tag{5}$$

where Ei is the emission of the entire trip, EC is the rail electricity consumption per passenger kilometer. And CI is the GHG emitted for producing or using a certain amount of electricity in $gCO_{2,eq}/pkm$. These are three necessary parameters to calculate rail emissions.

Firstly, the carbon intensity CI gets from the paper [17]. This paper calculates the CI in the entire WTW stage per Europe country. During the whole WTW stage, own electricity consumption, transmission, and distribution losses in the grid are all taken into count. The result is summarized in Figure 5. The location country of the rail in each step is identified to use the corresponding country's carbon intensity number. The result shows disparities across Europe because of different carbon electricity sources. The GHG intensities for electricity production were lowest in Sweden, and France because use a higher proportion of nuclear and renewable power to generate electricity compared with other countries[18]. And the intensity is large in a country like Poland, which means still highly relies on solid fossil fuels to generate electricity.

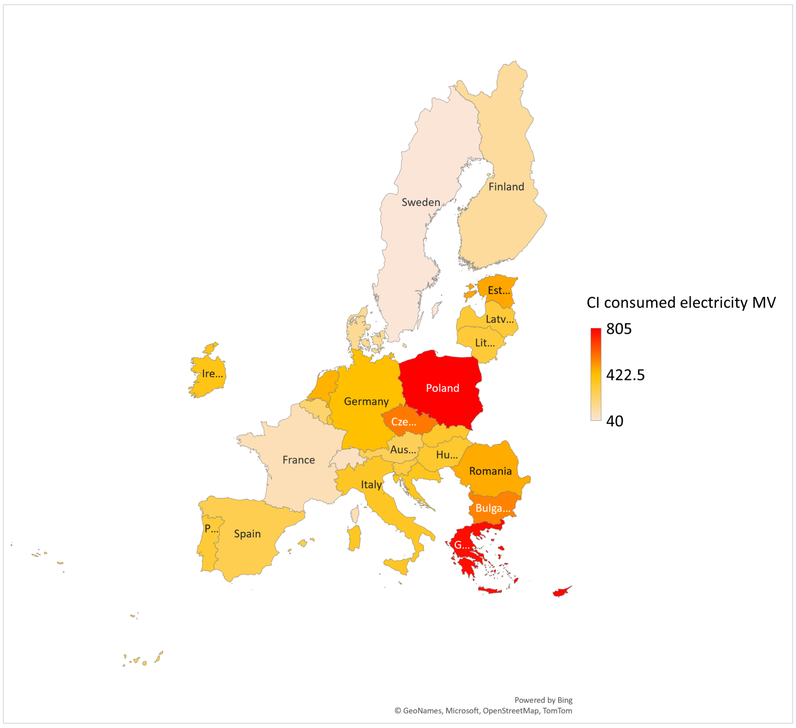


Figure 5. The EU-27 carbon intensity

Secondly, for EC, electricity consumption per passenger kilometer. It is highly related to the type of rail and the passenger occupancy rates. In this paper, the high-speed rail(HSR) is identified as the average speed of the whole trip is more than 150 km/h, or if the vehicle name provided in the GTFS result contains any of the acronyms of high-speed trains name in Europe. Table 2 summarizes the average European-level electricity consumption per passenger kilometer of the HSR and intercity rail under three occupancy-level circumstances.

Table 2. Rail well-to-wheel(WTW) factor

occupancylevel	Transport Service	Power type	Occupancy rate	Capacity	number of passengar	Energy consumption(kwh/pkm)	Source
High	High-speed	Electric	80%	500	400	0.039	[19]
High	Intercity	Electric	80%	500	400	0.0352	[19]
Average	High-speed	Electric	66%	500	360	0.057	[20],[21]
Average	Intercity	Electric	36%	500	180	0.089	[20],[21]
Low	High-speed	Electric	23%	500	115	0.19	[19]
Low	Intercity	Electric	23%	500	115	0.149	[19]

The average overall EU occupancy rate is around 66% for HSR and 36% for intercity. High-speed rail consumes more energy per train km than intercity, but as the average load factor of HSR is higher than intercity, they consume less energy on the passenger level. Two other scenarios are considered: low occupancy, and high occupancy. The low occupancy case is indicated as the average occupancy of 23% for ICE in Germany. The high occupancy rate is assumed 80% of the total seats. If the average electricity production emission factors are used(275 $gCO_{2,eq}/kwh$), the WTW emission for HSR is around 15.7 $gCO_{2,eq}/pkm$. The last parameter is the distance per step. The GTFS data contains the column containing information about the distance between each stop along the route. However, among some GTFS routes, data regarding the traveled distance is absent. Under that circumstance, rail travel distance can be calculated by summing the straight linear distance between two connected stations along the route.

For the whole life cycle analysis of the rail, the carbon emission of vehicle production and maintenance and disposal per passenger is around $1g/pkm$ of CO_2. The notable emission that counts for a significant part of the rail LCA emission is the emission of rail infrastructure. According to [13], most European countries carbon footprint of rail infrastructure for passenger traffic has an average value of $5g/pkm$. In total, an average $6g/pkm$ emission is added to the WTW to account for the total LCA emission in this paper.

C. Long distance Bus Model

The bus travel route model is built in the same method as the rail model. For the main long-distance bus company, the availability of data is as followed in Tabel 3. The Flixbus and BlaBlaBus have the complete up-to-date GTFS data, while data are not available for the Eurolines. However, Eurolines has already integrated into FlixBus now. Company ALSA serves as the primary bus company in Spain, connecting major cities within the country as well as offering cross-border routes to Portugal and France. These bus companies connect almost all the main cities in Europe which is considered sufficient for this study.

Table 3. Bus GTFS availability

company name	availability
Flixbus	Yes
BlaBlaBus	Yes
Alsa	Yes
Eurolines	No

Nowadays, The main bus fuel type is still diesel in EU-27, accounting for around 68.8% percent of new buses in 2021. For the long-distance bus company like Flixbus, they are still mainly run on diesel, with the electricity bus only running on a few routes. For the scope of this paper, only a diesel propulsion bus is considered. The traditional urban diesel buses have WTW emission factors in the range 55 to 112 g/pkm(average 87 g/pkm) [21], with an assumption of 12-15 people per bus. However, long-distance buses and coaches like Flixbus have a higher occupancy rate than the urban bus and it has frequent starts and stops compared to urban buses. The long-distance bus shows a better performance, with suggested emission factors in the range of 33–38 g/pkm from [22]. And this factor is considered constant in all EU countries and routes, the bus emission can be then calculated by multiplying the total distance with the GHG emission factor per passenger kilometer. Similarly, for bus routes, the missing bus distance in GTFS can be computed by adding up the linear distance between each bus stop.

D. Car Model

Car distance algorithm

As in Table 4, the length of the car routes is the result of an algorithm with great circle distances and deviation factors [23]. The deviation factor and the average speed are the estimations of the distribution of the distance to street classes (Motorway, Rural, Urban). Motorways provide a more direct and faster route for driving compared to urban roads. As the proportion of motorways in the total length increases for longer distances, cars have a higher average speed in such cases. Additionally, the deviation factor decreases due to the more direct routes on motorways during long-distance drives.

Table 4. Car speed and deviation factor

Linear distance	Deviation factor	Average speed
<=100 km	1.35	60 km/h
100 km - <=500 km	1.25	90 km/h
500 km - <=1000 km	1.15	95 km/h
>1000 km	1.1	100 km/h

However, for the case drive from Italy to Spain or the origin/destination is Denmark, the driving distance can not be approximated by the above method. Since the great circle distance is across the sea under those circumstances, the driving distance is much larger than the great circle distance. This route information is supplemented by a larger deviation factor of 1.5.

Car emission model

This paper calculates the emission of buses and cars by different propulsion systems. The five most common fuel types for the newly registered car during 2022 are discussed here for the car: petrol cars(36.4%), hybrid electric (HEV)(22.6%), diesel cars (16.4%), Battery electric (BEV) cars (12.1%), plug-in hybrid electric vehicle(PHEV) car(9.4%). Of the alternative options of diesel and petrol cars, hybrid electric cars experienced the most significant growth, with gradually enlarging the market percentage gradually enlarging from 4% to 19.6% in the past three years according to ACEA[24]. Buses running on diesel remained the most popular bus type. In this paper, only a diesel bus is considered.

Three occupancy rate is considered for the car. First is the average occupancy rate inside EU-27:1.6 passengers per passenger car, obtained by calculation from CE Delft[21]. Then, only one person per car and four people in one car are considered. Occupancy rates for passenger transport are considered constant across distance bands and propulsion systems for each vehicle category.

Table 5 summarizes the WTW and LCA emission as $CO_{2,eq}/pkm$ for each bus and car fuel type under the average occupancy rate circumstance. Notably, the emissions from long-distance buses have a substantial reduction when compared to emissions generated by all types of cars. The different car technologies' emission shows a significant difference. The BEV car has the smallest WTW and LCA emission per person compared with other car types. It largely reduces the emission compared with traditional diesel or petrol cars. For the entire LCA, BEV car has a larger emission related to battery manufacture and maintenance compared with other types, but it has a slightly lower emission for vehicle manufacture. Overall speaking, the difference between the LCA and WTW emission, representing the out-of-operation emission, is around 20 $gCO_{2,eq}/pkm$ for all the medium cars with different propulsion systems.

Table 5. Emission factors of different passenger transport modes in EU-27 for average occupancy rate

Transportation method	average WTW Emission factor($gCO_{2,eq}/pkm$)	average LCA Emission factor($gCO_{2,eq}/pkm$)	reference
Long distance bus diesel	35	40	[22]
Private car diesel	139	159	[25],[26]
Private car petrol	149	169	[25],[26]
Private car HEV	85	106	[22],[25],[26]
Private car PHEV	69	91	[25],[26]
Private car BEV	52	75	[25],[26]

E. Emission equivalent time

For considering both the time and emission effect, the least travel time option does not always lead to the least emissions for the trip. For the optimal trip, a trade-off exists between travel time and emission. Equation 6 is introduced to consider both the weight of time and cost.

$$T_{equivalent} = \beta_{em} \times EM + TT \tag{6}$$

where β_{em} is the emission equivalent time, TT is the travel time, EM is the travel emission. The optimal route has the smallest $T_{equivalent}$. Aziz and Ukkusuri [27] found the trade-off value β_{em} ranging from 0.089 minutes/kg to 8 minutes/kg for passengers. An average of 3.04 minutes per kg CO_2 for non-work trips and an average of 2.83 minutes per kg CO_2 for work trip passengers who are more sensitive to time. In a 500km route, the train and airplane emission difference of approximately 80 kg, means work passengers willing to travel around 3.7 hours longer to save this emission, while average non-work passengers are willing to travel 4.1 hours longer. On average, non-work passengers are willing to travel longer time to save emissions compared with work passengers.

III. Experiments and Results

41 popular main city centers across EU-27 are chosen as the location to conduct the calculation as shown in Figure 6.

Figure 6. The city center location map

The nearest major airports of these main city centers are taken as the air travel origin/destination. Paris is served by two primary airports, while the Milan metropolitan area has three main airports, resulting in a total of 44 airports being considered for air travel options. A full list of chosen airports is included in Appendix B. To ensure passenger travel quality, a maximum travel time of 800 minutes between the origin and destination was set.

For public ground transportation, this paper takes advantage of the GTFS feed in March 2023 for ground transportation route mapping. However, for air travel, the 2023 Eurocontrol data is not available yet, so the March 2019 Eurocontrol data is used for air travel information.

The result analysis in this section first discusses transport networks inside EU-27 by different transport methods. Subsequently, the transportation travel time, distance, and environmental impact are compared at an individual passenger level. Furthermore, we explore potential ground transportation routes to substitute air travel and its emission saving taking the trade-off between emissions and travel time into account. The overnight train/bus option is addressed separately due to its unique characteristics. Finally, the model's output sensitivity to the input parameters is investigated.

A. Transport Network

Between these 41 city center pairs, a total of 820 distinct origin-destination pairs exist, covering the major travel routes inside EU-27. The distances between the centers of these cities have been classified into different bands, as in the following Figure 7. A total of 720 connections, which is approximately 87.8% of the total, have a distance below 2000km, which is considered the maximum feasible range for the rail to potentially

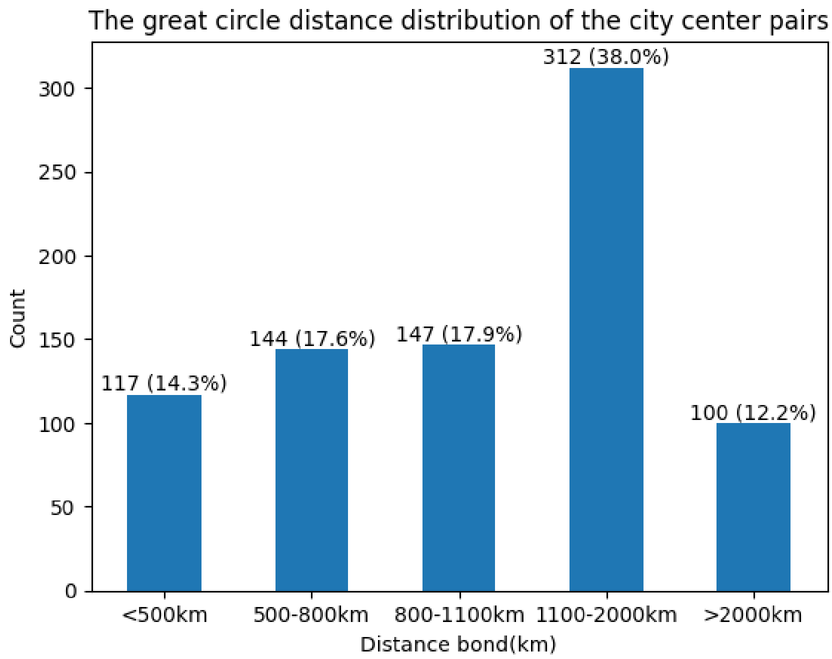


Figure 7. The distribution of great circle distances between 41 city centers

replace air travel by previous research[28]. Approximately 31.9% of the analyzed routes fall within a distance range below 800km. Chiara et al.[19] indicate 800km represents the threshold for High-Speed Rail (HSR) operations to be most competitive with air travel in terms of time.

Figure 8 shows a comparison of the traveled distance between different transportation methods. Air travel is characterized by the shortest travel distance,

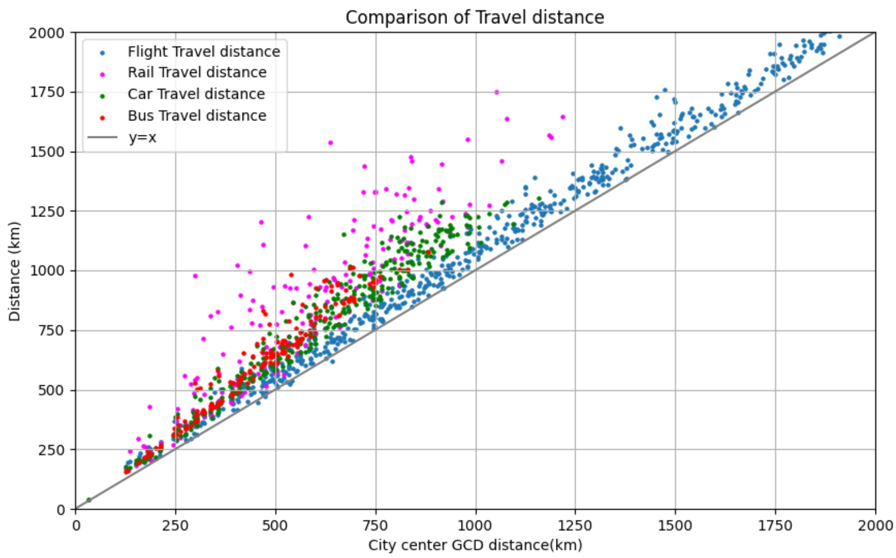


Figure 8. The travel distance comparison between different transport methods

which shows a linear relationship with the great circle distance of the city's center. On the other hand, bus and car travel display similar distances, with buses covering slightly longer distances than cars. The rail travel distance, however, exhibits a greater variance due to variations in the rail connection quality. In routes with no direct rail connections, the rail distance can be significantly longer compared to the distances covered by buses and cars. For example, when traveling between Marseille and Nantes in France, a rail journey with a transfer in Paris results in a rail distance that is approximately 20% longer than the corresponding car route. Conversely, in routes with direct rail connections, rail travel distances can be more advantageous. For instance, between Paris and Amsterdam, the rail distance is actually shorter by approximately 50 kilometers compared to the distance covered by a car. These results highlight the importance of considering the specific route and transportation mode when evaluating travel distances, as it can significantly impact the resulting travel emissions.

Figure 10 presents a comparison of all possible connected routes among the selected city pairs. The analysis reveals notable differences in network density between air travel, bus, and rail networks within EU-27. The air travel network presents significantly higher density, allowing for direct connectivity between a total of 650 city pairs. The accessibility offered by cars extends to almost all routes, however, with only around 343 routes remaining feasible after removing the routes with travel times exceeding 800 minutes(around 13.3 hours). Regarding public ground transportation, the rail network enables connectivity for 211 routes (refer to Figure 9), whereas the bus network allows for connections on 151 routes. The bus network has a higher proportion of direct routes compared to rail transport, with 140 routes directly connected by bus and 82 routes directly connected by rail.

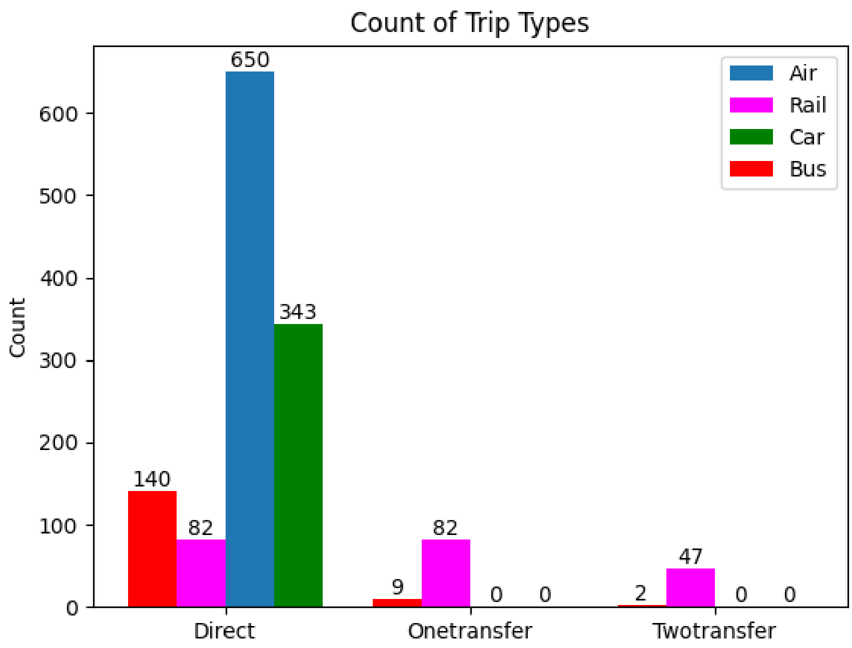


Figure 9. The count of trip types

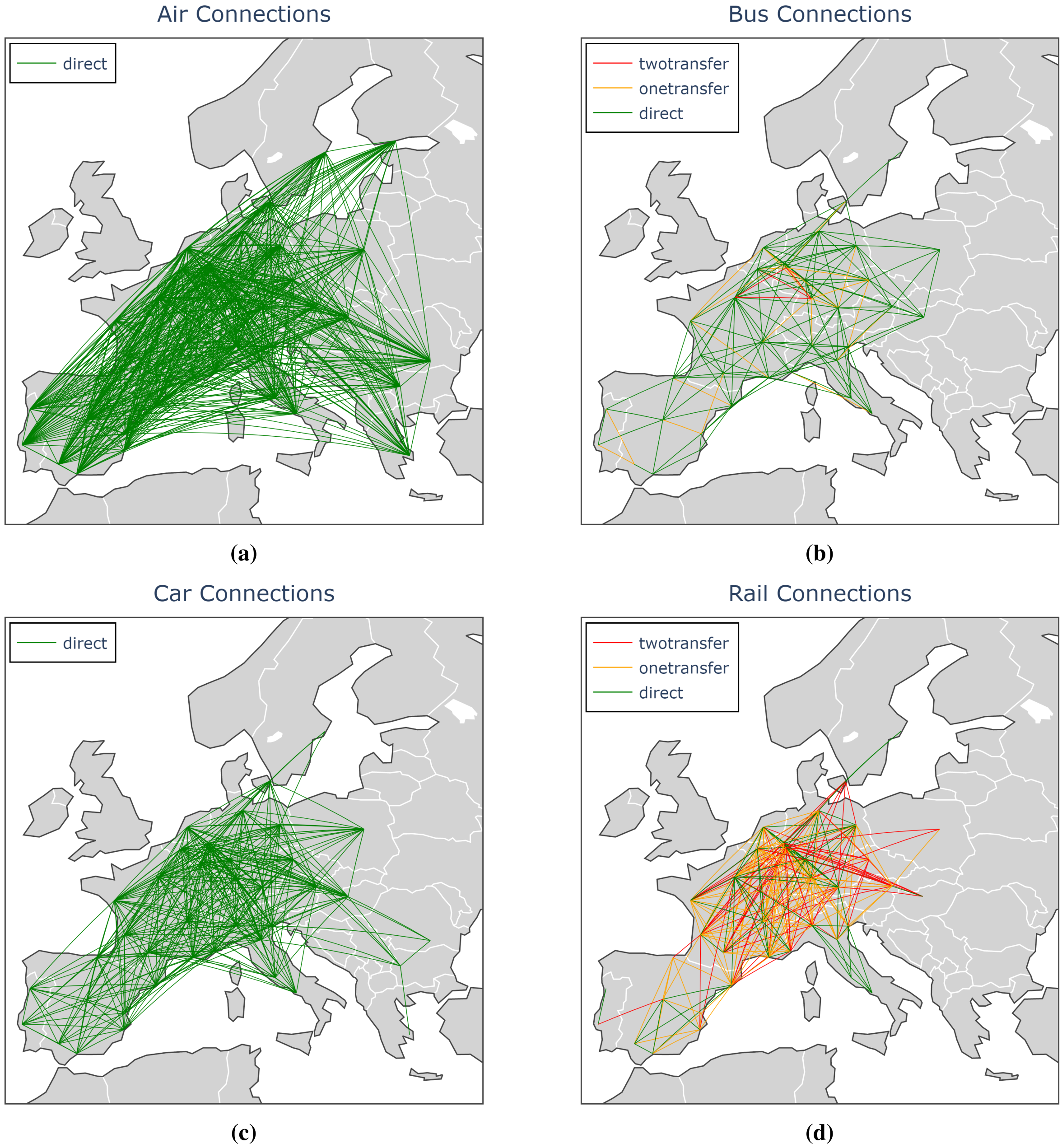


Figure 10. Network comparison

The HSR connections inside EU-27 are shown in Figure 11. In calculating the emission, whether a train is an HSR is determined by if its name is within the HSR train lists in Europe, like ICE in Germany, TGV in Paris, and TRENITALIA in Italy. By definition for the HSR from Demiridis & Pyrgidis [29], HSR should reach the maximum achievable running speed in excess of 200 km/h and an average running speed in excess of 150 km/h. When we take a deeper look at the average speed of routes, it shows disparities across Europe.

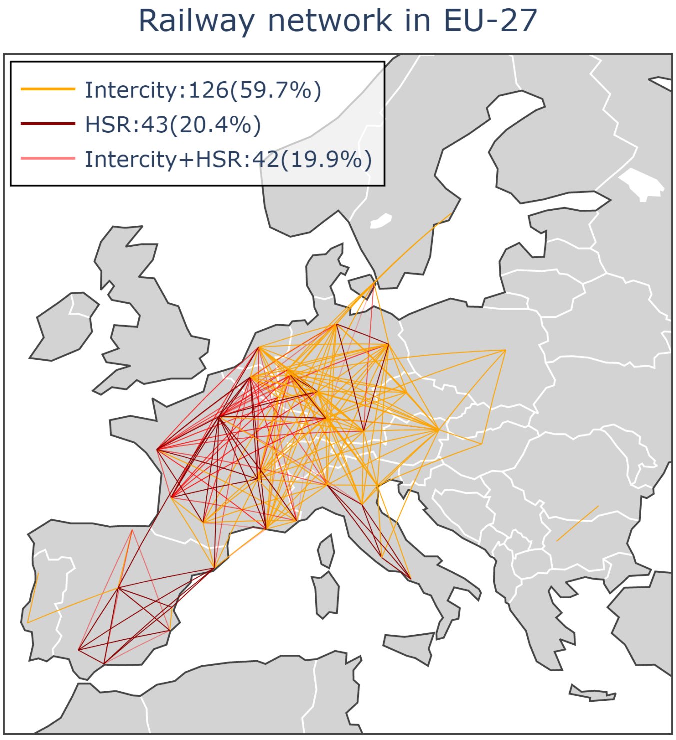


Figure 11. The High-speed rail network between selected points, classified by if the speed >150km/h

43 routes(24.9%) can be totally connected by train speed higher than 150km/h. Most of these routes are within France, Spain, and Italy. These countries have the highest-quality HSR network, with almost all HSR routes satisfying the definition of reaching the average speed of 150km/h. Although Germany has an HSR network by train ICE connecting all the main German cities discussed in this paper, most of the routes are not connected by an average train speed higher than 150km/h. Of 43 HSR routes, there only 11 routes are cross-border HSR. Renfe-SNCF is one of the companies that provides some crosses border routes between France and Spain, which mainly connected the cities between Barcelona with major France cities.

B. Transport time comparison

To ensure a valid modal shift, it is essential for the quality of transportation to be similar to passenger expectations. This discussion focuses on one key factor of transport quality: time. While air travel has no direct competitor in terms of actual in-flight time, when considering additional factors such as check-in procedures, boarding time, and commuting time between cities and airports, the total airport travel time significantly increases.

The analysis of travel time reveals that rail travel emerges as the most time-efficient ground transport method. On certain routes spanning distances under 800km great circle distance, rail travel time can even be smaller than air travel time, as illustrated in Figure 12. The longest route is for rail to substitute air from Paris to Marseille by TGV in France, the travel time is 218 minutes for an 800 km rail travel distance, similar to air travel of 300 minutes. Both bus and car travel times can be shorter than air travel time for distances below 400km. The car has a driving The bus travel time tends to exceed that of car travel due to frequent stops and less direct routes. As in Figure 13, when the extra time is one and a half hours, 105 routes inside the EU can be traveled by rail, while 88 routes by car.

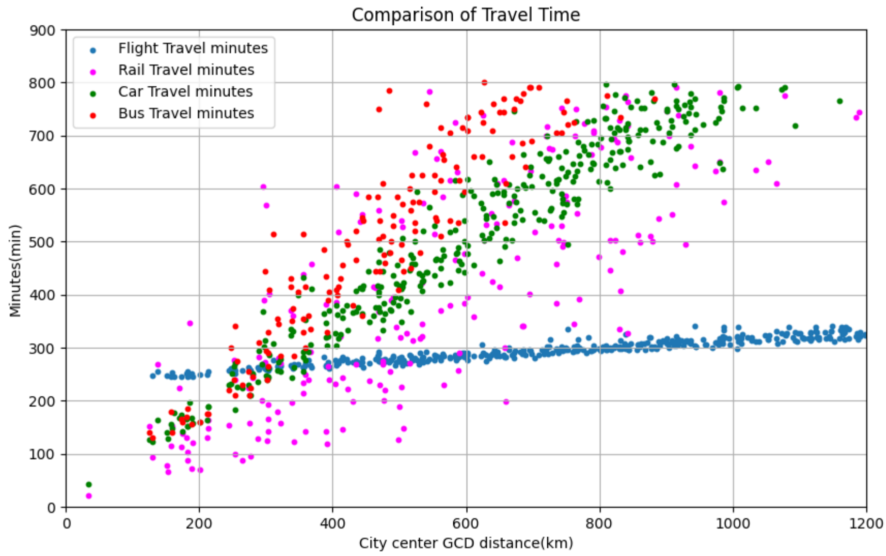


Figure 12. The time comparison between different transport methods

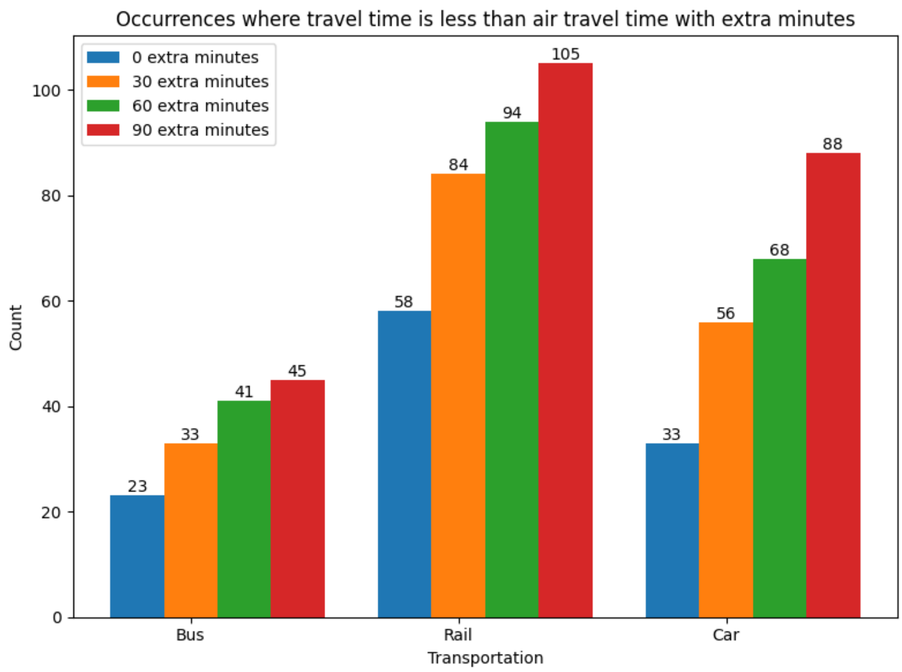
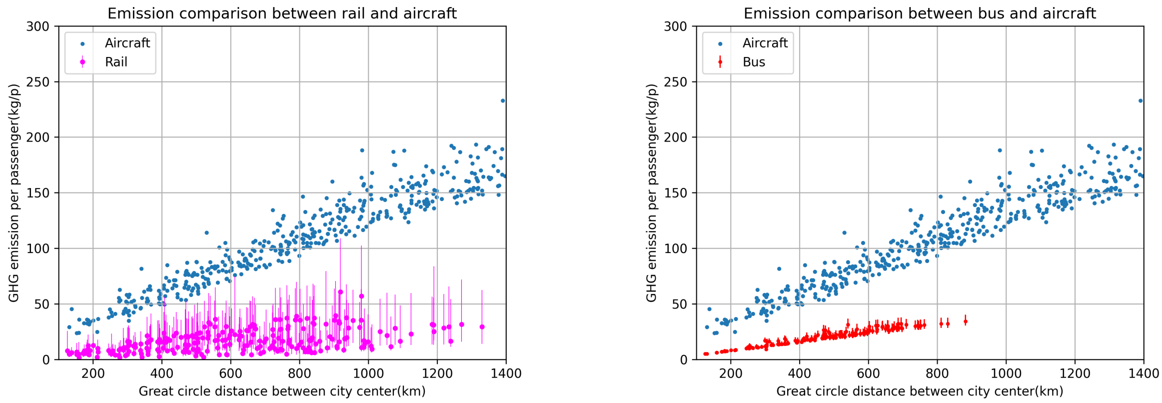


Figure 13. Occurrences where travel time is less than air travel time with extra minutes

C. Transport WTW and LCA emission comparison

WTW emission

Rail, bus, and car compared with aircraft for WTW emissions separately in Figure 14 and Figure 15. The error bars represent the uncertainty in emissions resulting from the variability in energy consumption values. Notably, rail emissions exhibit significant variation due to differences in passenger occupancy rates from 23% to 80% across various rail lines throughout Europe. Conversely, long-distance coach buses are assumed to have a more consistent occupancy rate, resulting in less variation in per-passenger energy consumption.



(a) The WTW emission comparison between rail and air

(b) The WTW emission comparison between bus and air

Figure 14. The WTW emission for rail and bus compared with air travel

The comparison between rail, bus, and aircraft emissions reveals that the overall emissions from rail and bus transportation are lower than those from aircraft, even at low occupancy levels. Even at the same distance, the rail emission exhibits different value because of different type of train or across countries that has different carbon intensity.

Figure 15 examines the emissions of cars considering three occupancy scenarios and five fuel types. When four people travel in a single car, the emissions per passenger are consistently lower than those of aircraft for all fuel types. In the case of an average car occupancy of 1.6 people, petrol and diesel car emissions exceed those of aircraft, while emissions from hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV) remain lower than aircraft emissions, assuming the maximum driving time for cars. When only one person occupies the car, both petrol and diesel car emissions consistently surpass aircraft emissions, with the emission gap widening as the travel distance increases. Notably, HEV, PHEV, and BEV emissions are comparable to aircraft emissions, with BEV emissions being lower. In summary, there are five scenarios where cars exhibit higher emissions than aircraft: petrol and diesel cars with one occupant, HEV cars with one occupant, and petrol and diesel cars with an average occupancy of 1.6 people.

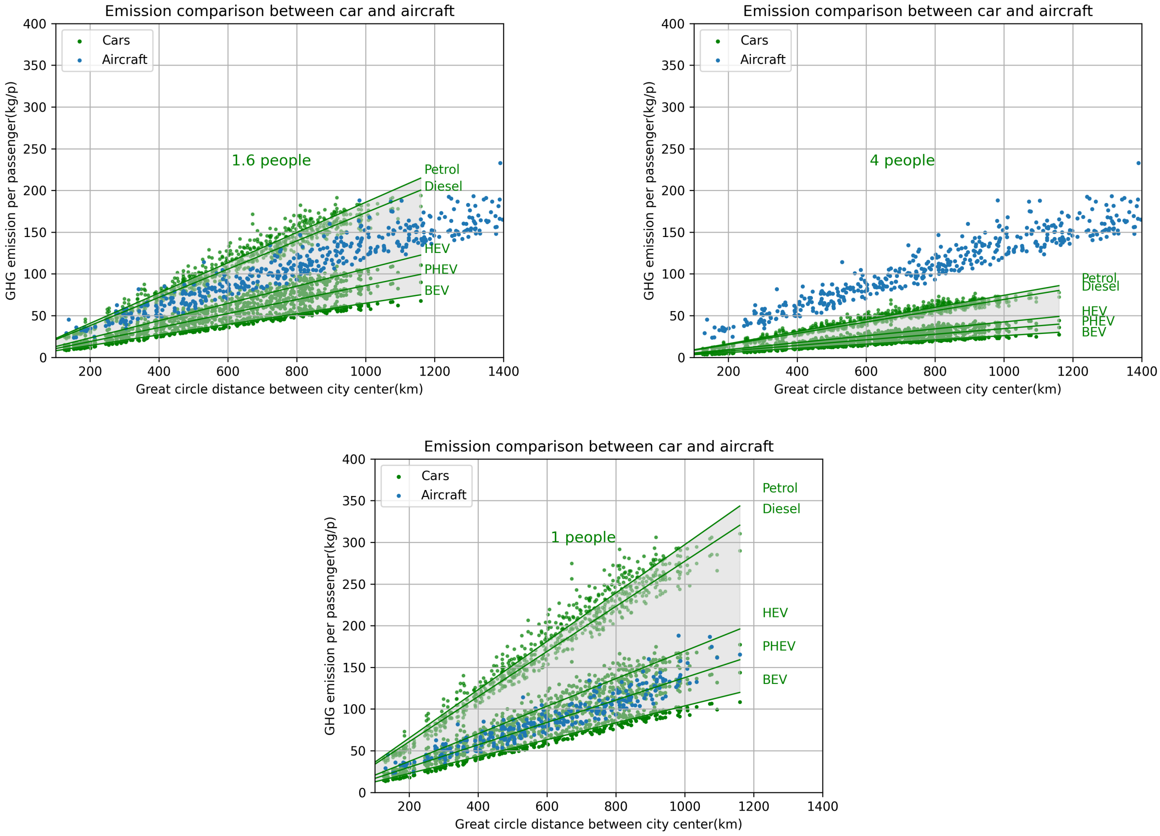


Figure 15. The WTW emission comparison between car and air

The rail is the best option to provide similar travel time to aircraft. However, rail emissions may not always be the lowest among the transportation modes. In general, bus emissions tend to be higher than rail emissions in most situations. However, in countries with high carbon intensity, such as Germany and the Netherlands, train emissions can surpass those of buses. Additionally, bus emissions can be lower than rail emissions in cases where the rail distance is less direct or when rail occupancy is low.

Analyzing car emissions reveals that cars can only achieve lower emissions than rail when there are four people in the vehicle, specifically with HEV, PHEV, or BEV propulsion systems. However, when considering petrol or diesel-powered cars, even with four people in the vehicle, their emissions still exceed those of rail in all the routes examined in this study, as depicted in Figure 16. This emphasizes the environmental advantages of using electricity-powered cars over petrol or diesel-powered cars and highlights the need for sustainable alternatives in car manufacturing to effectively reduce emissions.

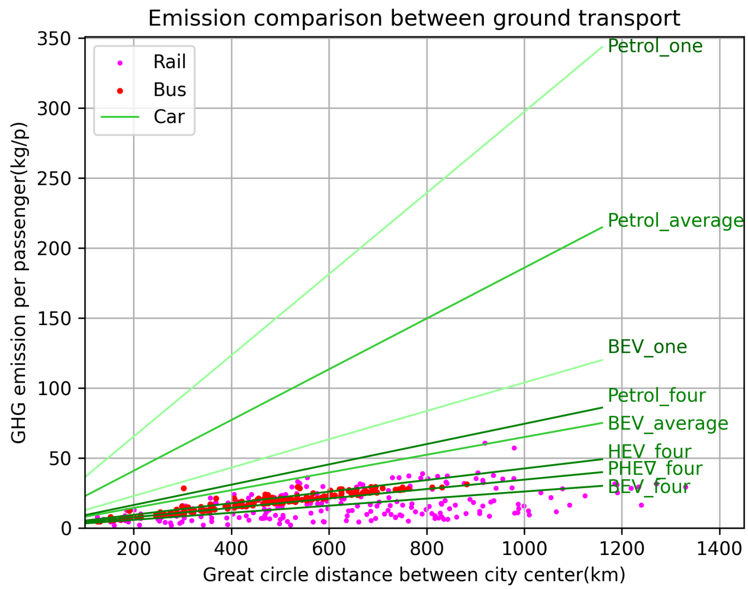
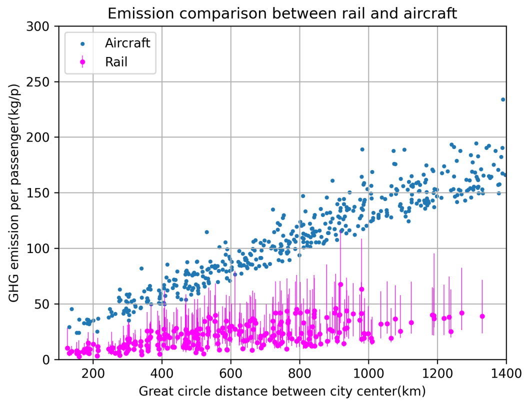


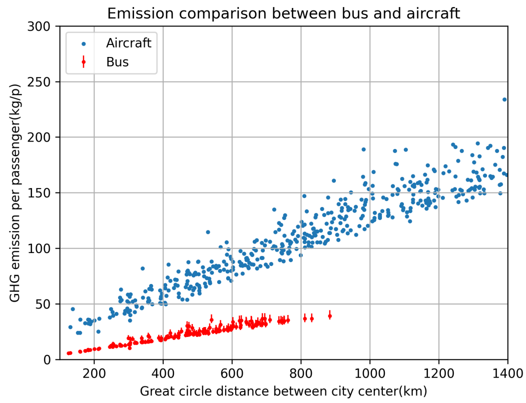
Figure 16. The WTW emission comparison between ground transport

LCA emission

The following discussion incorporates the life cycle assessment for the transportation methods. The rail and bus emission is still lower than the air travel emission as in Figure 17 for all the routes.



(a) The LCA emission comparison between rail and air



(b) The LCA emission comparison between bus and air

Figure 17. The LCA emission for rail and bus compared with air travel

Nevertheless, the life cycle assessment emissions of car travel experience a substantial increase due to significant vehicle production and maintenance emissions per passenger. In scenarios involving an average of 1.6 people, BEV and PHEV continue to exhibit lower emissions compared to air travel, while HEV now demonstrates emissions comparable to those of air travel. In situations where only one person utilizes the car, LCA emissions from all fuel types surpass those of aircraft emissions. However, with four individuals in a car, emissions from all car types still remain lower than those associated with air travel.

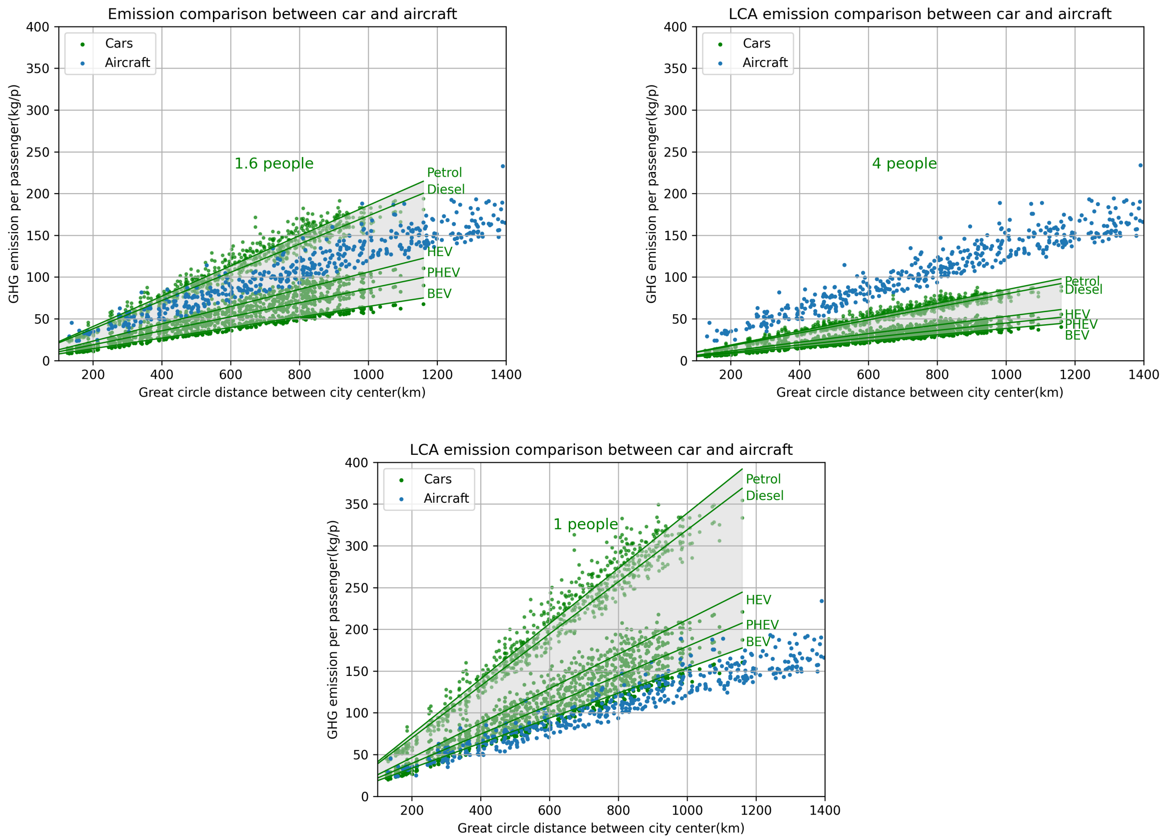


Figure 18. The LCA emission comparison between car and air

D. Possible substitution

The choice of the route for passengers involves a trade-off between emissions and travel time. This trade-off is influenced by the emission equivalent time value, denoted as β_{em}, which reflects the importance passengers place on emissions in their decision-making process. A value of 0 for β_{em} indicates that passengers prioritize minimizing travel time, not taking emissions reduction into consideration. Conversely, a higher value of β_{em} indicates that passengers assign greater weight to emission reduction when selecting their mode of travel.

In the emission calculation, it is assumed that the occupancy level for all transportation modes is at its average value. And the car powered by HEV is chosen to investigate its role of replacing air travel because of its lower emission compared with petrol/diesel and it has a rapidly increasing market share in recent years.

Figure 19 illustrates the impact of the emission equivalent time cost on the selection of routes. When β_{em} is 0, indicating only focus on minimizing travel time, approximately 600 out of the 710 analyzed routes in the EU-27 show shorter travel time by air compared to ground transportation. As β_{em} increases, representing an increasing emphasis on emissions reduction, the number of routes choosing air travel decreases, while rail travel experiences the largest increase. The number of bus trips also sees a slight increase. When passengers solely consider travel emissions, disregarding travel time (represented by an infinitely large β_{em} value), the total number of rail routes is 184 out of the total 710 routes, while air travel drops to approximately 341 routes.

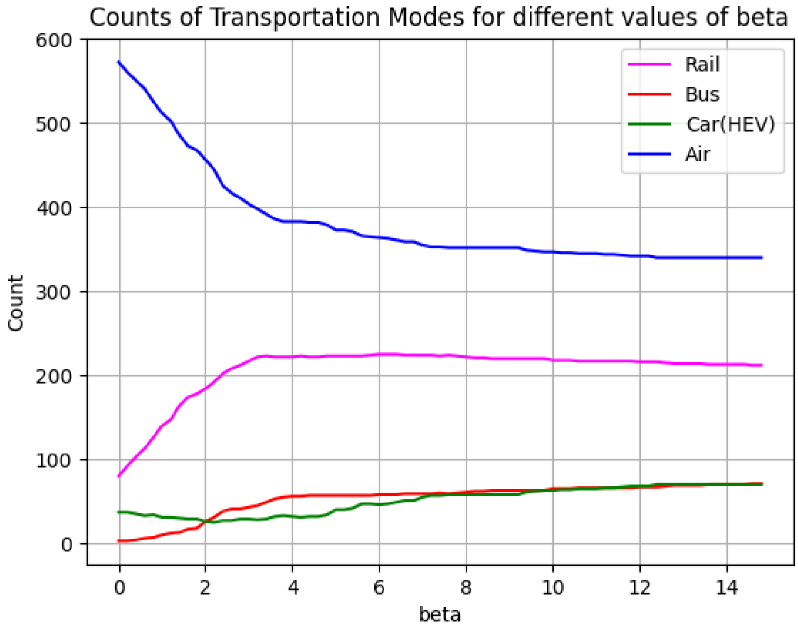
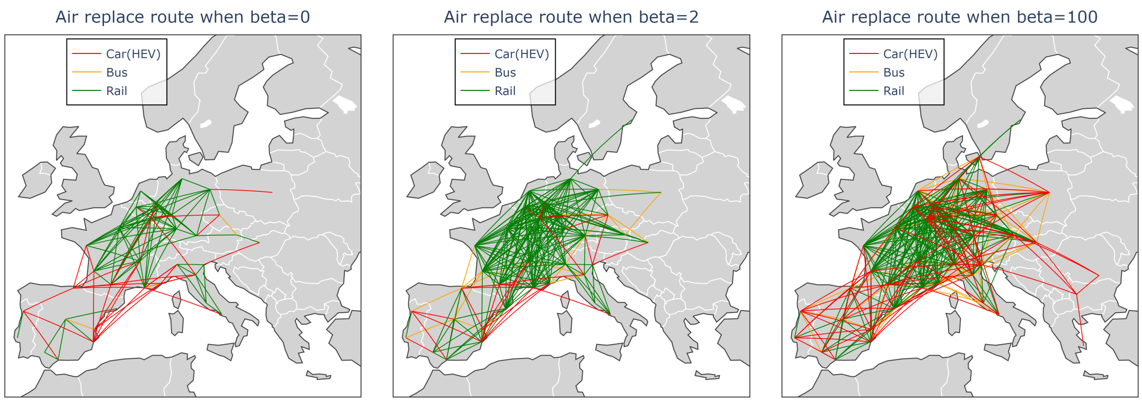


Figure 19. Counts of Transportation Modes for different values of beta(emission equivalent time). When beta is larger, it means passengers put more weight on reducing emissions. Therefore, the air travel number drops, while the ground transportation trip number increase

Figure 20 illustrates the ground transportation routes that could substitute air travel as beta values increase. With the rise in beta values, a greater number of routes become viable alternatives to air travel. The majority of rail-based replacements are concentrated within countries like France and Germany, where the quality of rail connections is high. In Eastern European nations where rail connections are lacking, cars continue to play a significant role in replacing air travel.



(a) **(b)** **(c)**

Figure 20. The trip selection under different beta values (emission equivalent time). When the beta is larger, more trips will be substituted by ground transportation

As demonstrated in earlier emission comparisons, air travel consistently results in higher emissions compared to buses, railways, and Hybrid Electric Vehicles (HEV). The actual reduction in total emissions achieved by transitioning from air travel to the most environmentally friendly ground transportation option can be approximated using the following equation:

$$E_{total} = (E_{airtravel} - E_{alternative}) * a * percentage \tag{7}$$

where E_airtravel represents the emissions from air travel, E_alternative denotes the emissions associated with the lowest total equivalent transportation T_equivalent from Equation 6. If air travel happens to possess the smallest T_equivalent, the emission savings will be zero. a stand for the number of air passengers on the specific route, sourced from the Eurostat database for the year 2022[30]. The "percentage" indicates the proportion of passengers adopting this model to choose the routes with the minimum T_equivalent. In essence, this model is designed to assist air travelers in selecting the optimal travel method, taking into account both emissions and travel time effects. The emission of air travel over a year, as a function of beta, is depicted in Figure 21.

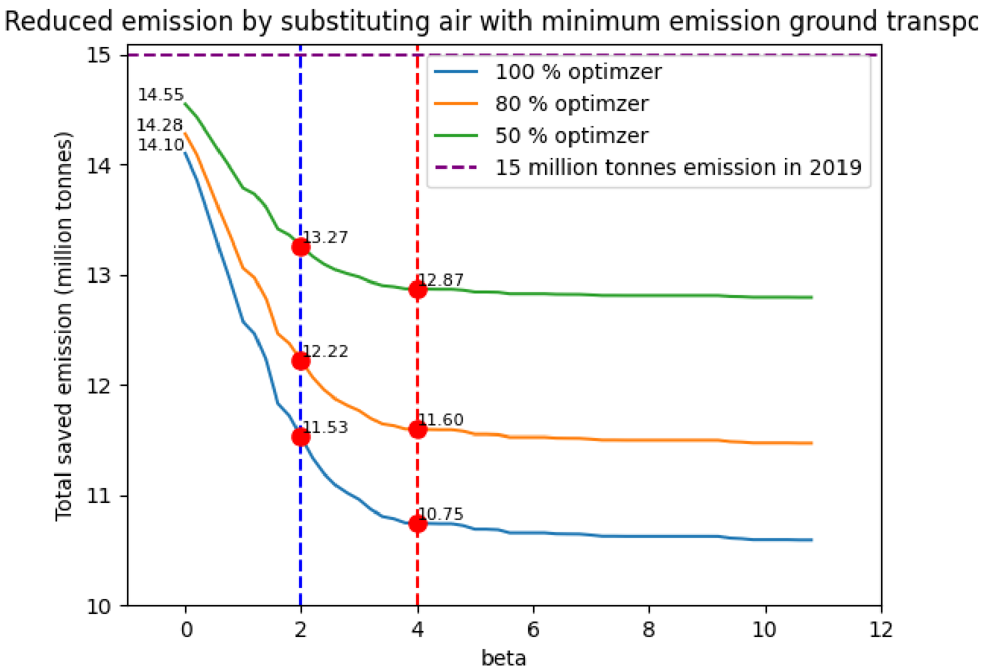


Figure 21. The emission reduction in relation to beta(the emission equivalent cost). Three circumstance are taken, 100%,80% or 50% of air travel passengers using this model

Three scenarios were considered to estimate the emission reduction: 100%, 80%, and 50% of total air passengers choosing to use this model. Despite the long travel time of air travel, passengers may still choose air travel for various reasons, including cost considerations, connection flights, or easier access to airports. With a complete shift of 100% passengers only on the routes where ground transportation has shorter travel minutes than air travel, approximately 0.89 million tonnes of greenhouse gas (GHG) emissions can be saved. In an extreme hypothetical scenario where 100% of passengers shift from air to ground transport(neglecting the impact of travel time, making beta undefined), approximately 4.5 million tonnes of GHG emissions can be saved annually. Considering that the total aviation emission for intra-EU flights in 2019 was 15.1

million tonnes, this result suggests that around one-quarter of emissions could be saved by a complete shift of passengers from air to ground transport where ground transportation has a smaller T_equivalent than the air. Setting beta at 2 minutes/kg, signifying passengers' willingness to extend travel time by 2 minutes in order to mitigate 1 kg of greenhouse gas (GHG) emissions, the adoption of this model by all air passengers could lead to annual emissions being reduced to around 11.53 million tonnes. Alternatively, with passengers open to spending 4 minutes per kilogram of GHG emissions, the potential emission reduction for intra-EU air travel could reach 4.25 million tonnes, resulting in a total emission of 10.75 million tonnes GHG in one year.

E. Overnight train and bus

From previous results, we can see that the emission can be largely reduced by replacing the air with the bus/train/car. However, the replacement is largely restricted by offering similar travel time. Passengers who choose overnight trains/buses are compensated for time and cost by saving the cost of hotel accommodation, which enlarges the network of substituting air with overnight trains/buses.

If only the direct route is considered, there are 9 main overnight bus routes inside EU-27 by Flixbus. There are several rail overnight companies in EU-27, however, there are currently no complete overnight GTFS data available.

Taking a night jet route from Munich to Hamburg as an example, the night jet takes 11 hours to arrive, during the day time the ICE is about 6.5 hours, while the total air transport time is 4.8 hours, For passengers who do not want take 2 hours more during the day compared with air transport, the night train can take as a solution. UIC [31] reports the night train result shows 20% higher emission than the daytime train on the same route. Between Munich and Hamburg, nearly 105 kg GHG per passenger can be saved by transferring from air to night train. From the connection map as in Figure 22, the night train connects well in eastern countries. The daytime rail connection in the eastern is totally uncompetitive with air travel in time due to its low quality. By night train, it can play a role in connecting Eastern Europe cities to compete with air travel. Further research can try to gather the Eastern night train database to study its effect on competing with other transportation methods.

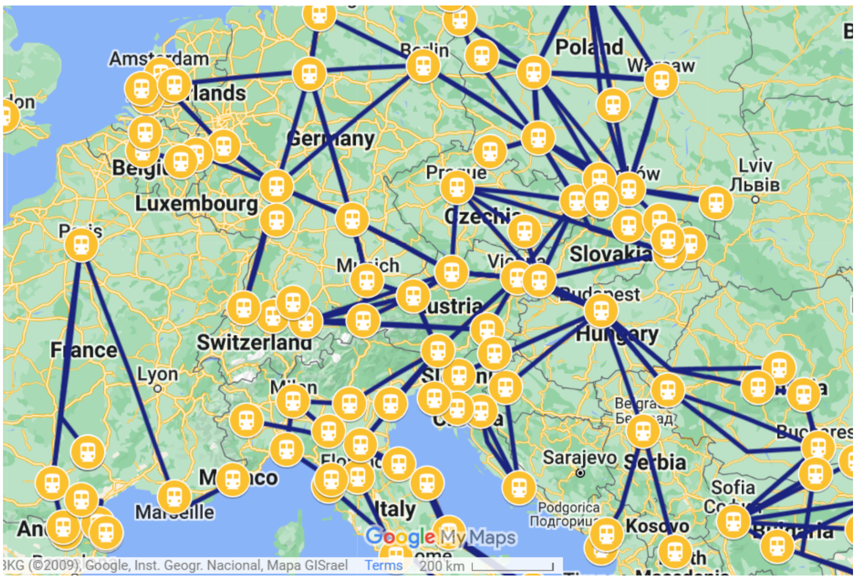


Figure 22. The night jet connections in EU-27 by Eurail[16]

F. Sensitivity analysis of aircraft occupancy

Three masses are defined at 70%, 80%, and 90% of the aircraft's maximum take-off weight to reflect the output sensitivity to the take-off mass as in Figure 23.

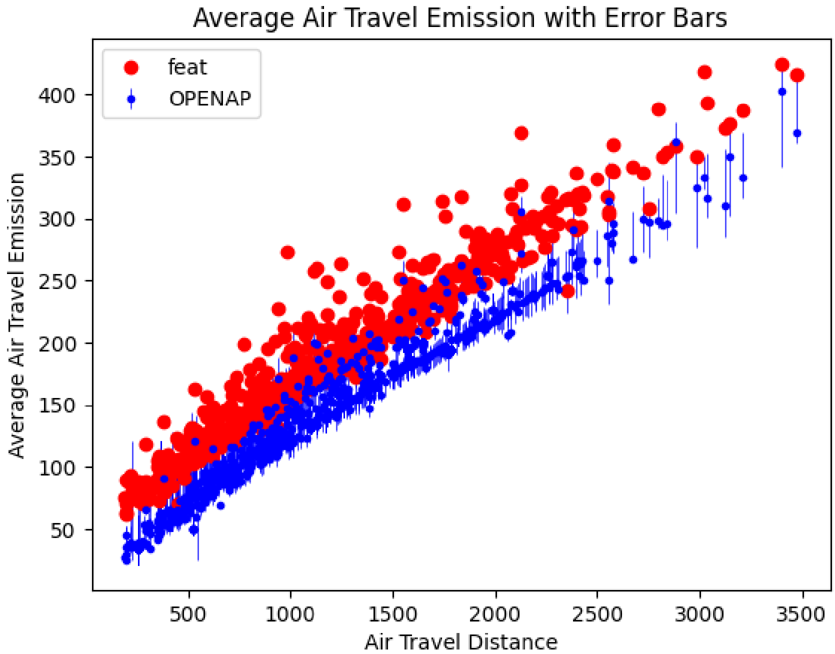


Figure 23. The emission result comparison between OPENAP and FEAT

When comparing the results of the FEAT model [32] with the OPENAP model, it is observed that the FEAT emission results are slightly higher than the OPENAP results. When considering a take-off mass of 90% of the maximum take-off mass, the FEAT and OPENAP results are more closely aligned compared to the other two weight situations.

G. Validation of the model

To validate the emission calculation reliability, the mean travel time and emission were compared to the online Ecopassenger[23] calculator as in Table 6.

Table 6. GHG emission and time comparison result between the model and Ecopassenger calculator

method	transportation emission($kgCO2e/pax$)	EHAM-EDDF	LFPO-LFMN	LEMD-LEBL	LFPO-EHAM
Model	Rail	16.6	5.3	9.2	8.6
Calculator	Rail	15.8	7.2	11.1	9.2
Model	Aircraft	121.2	122.1	99.8	100.3
Calculator	Aircraft	131.4	127.1	115.2	85.7
Model	Car	61.5	129	86	74.5
Calculator	Car	63.2	111	86	71.1

The diesel car with an average of 1.6 people shows high consistency with the Ecopassenger results, which assume 5.3L/100km fuel consumption for a medium diesel car with 1.5 people. The rail results show a slight deviation from the Ecopassenger model, which could be attributed to two possible factors. First, there may be some discrepancies in the distance calculations. Secondly, Ecopassenger incorporates specific values per passenger-kilometer for different types of train services in seven countries, whereas our research assumes uniform train electricity consumption across Europe, with differentiation only between high-speed rail (HSR) and regular rail. Regarding the air travel results, the Ecopassenger uses the emission factor for different aircraft during different distance bands. The result shows consistent with the OpenAp result, and the Ecopassenger result is more similar to the 80% or 90% take-off weight assumption in OpenAp. Overall, the model developed a reasonable model and consistence with previous research.

IV. Discussion

This section provides further elaboration on the strengths and weaknesses of the constructed model, discusses the limitations of the results, and offers suggestions for future development. Additionally, recommendations are provided for various stakeholders, including individual travelers, travel operator companies, and policymakers to promote sustainability within the EU-27.

A. Insights into the transportation model based on GTFS

The GTFS model developed in this study presents a notable advantage by eliminating the need for closed-source or manually-collected methods to compute actual travel routes. These conventional approaches are challenging to replicate and are constrained by request limitations. In contrast, the GTFS databases utilized in this research are entirely open and freely accessible, enabling extensive calculations across Europe without any restrictions.

Regarding calculation speed, it is primarily depend on the size of the employed GTFS database. In this investigation, the combined GTFS databases of 13 countries amount to approximately 3 GB. When identifying rail routes among 820 city pairs within EU-27, a total of roughly 25,000 potential connections were established within a single day. Users can select their preferred routes based on travel duration, transfer times, departure or arrival times. The calculation time for this process using the model is approximately 3 hours. In comparison with Google Route API, which offers only 40,000 free requests per month, the calculation capacity of the built model is significantly enhanced.

Accessing GTFS databases is also straightforward. Platforms like Transitland [33] collect extensive GTFS databases from various operators, facilitating easy user access and downloads. Another notable strength of the model developed in this study is its flexibility when contrasted with closed-source APIs. It allows for more customized settings based on user preferences, such as selecting specific agency routes, imposing transfer time or location limits, or requiring specific train types for route completion.

However, a notable limitation of this public ground transport model is the regional availability of GTFS databases. The GTFS data for countries like Portugal, Italy, and certain Eastern European nations is incomplete, posing challenges when applying the model in these regions. Additional information from alternative sources becomes necessary. Presently, the most comprehensive GTFS databases are accessible for countries like the Netherlands, Germany, and Spain, which extensively cover urban and long-distance bus/rail routes. This accessibility ensures the reliability and accuracy of the results of research within these countries. Nowadays, more operators are contributing their GTFS data, enhancing the overall dataset's comprehensiveness. In the future, increased completeness and accuracy of GTFS data will simplify research efforts.

Another drawback is that the GTFS database might not be as user-friendly as an API for route computation. The GTFS data necessitates linking multiple text files and comprehending file structures to find the desired routes, while APIs offer more straightforward usage. Additionally, the GTFS dataset contains data errors. For example, inconsistencies in the "shape dist traveled" column require calculating the traveled distance by summing up distances between stops. Nonetheless, entities like gtfs.pro[34] and Transitland[33] are actively visualizing and collecting GTFS data, along with enhancing its accuracy.

In summary, despite these limitations, the GTFS model provides users with an open approach to computing travel routes, offering flexibility for sustainable transportation research.

B. Result restriction

The model does exhibit several limitations in its outcomes. In the context of rail transport, distinct carbon dioxide emissions are computed for two train types: high-speed rail (HSR) and intercity rail, considering three occupancy rate scenarios. However, even within the HSR and intercity rail classifications, carbon intensity can significantly vary across lines due to factors like infrastructure, rolling stock, number of stops, and occupancy rates. For a more precise estimation of rail Well-to-Wheel (WTW) emissions, future research should consider improving accuracy in estimating rail energy consumption.

Furthermore, during the calculation of Life Cycle Assessment (LCA) emissions, the emissions related to rail infrastructure exhibit substantial differences from one line to another due to factors like the load factor and transport volume serviced by the network. This study employs an average value suggested by the International Union of Railways [35] to account for an additional 5 $gCO_{2,\text{eq}}/pkm$ to incorporate carbon costs associated with rail infrastructure, maintenance, and manufacturing. However, other research [36] estimates the average footprint at 18.24 $gCO_{2,\text{eq}}/pkm$ based on transport density and annual emissions in Spain. Previous LCA studies on rail emissions also display a substantial range from 4 $gCO_{2,\text{eq}}/pkm$ to 59 $gCO_{2,\text{eq}}/pkm$. Overall, the environmental impact of public transport infrastructure construction and maintenance can vary significantly depending on the specific route. A case-by-case analysis is necessary to determine the actual impact of LCA on the environment.

In terms of transportation travel time, this study selects the minimum travel time within a day. However, actual travel durations can vary based on passengers' chosen departure and arrival times. Future model calculations could be extended to incorporate passengers' preferences for departure and arrival times, and the sensitivity of travel minutes with respect to departure/arrival times can be examined.

Regarding aircraft emission calculations, the passenger occupancy rate is set at 81% for all take-off mass conditions, and three different take-off mass is considered. Notably, the take-off mass is interconnected with occupancy, an aspect that is not fully accounted for in this paper as a consistent occupancy rate is used. Future advancements could involve adapting the Openap model to factor in how occupancy rates influence take-off mass and the resulting fuel consumption. Drawing from the previous fuel estimator FEAT model [32], flight missions might need to be simulated iteratively to compute fuel consumption for specific mission distances.

C. Model future development

At present, the GTFS dataset is provided by transit operators or government departments, each with its own schemes for identifying and labeling data. The same stop or trip may have different "stop_id" and "trip_id" values depending on the provider's nomenclature. This inconsistency arises when incorporating the GTFS dataset from across Europe. Simplifying the model would be greatly facilitated if data identification and labeling schemes were standardized throughout Europe.

Beyond carbon emissions, factors such as travel cost and the reliability of travel time play crucial roles in influencing passengers' route preferences. Integrating these components into the model would offer a deeper insight into the trade-offs associated with different transportation choices.

This paper only considers the shift of the entire trip, without taking potential intermodal cooperation into account. In subsequent developments, the model could be refined to account for possible cooperation between different modes of transportation.

Furthermore, when assuming the shift of passengers from air transport to ground transportation, it is essential to account for the capacity of ground transportation in terms of passenger volume. Estimating the ground transportation capacity can be achieved by calculating the frequency rate and multiplying it by the maximum load factor.

D. Recommendations and actions to improve the environmentally sustainable by modal shift

Recommendations to traveller transportation choice

Aircraft have shown higher emissions compared with rail and bus, for passengers, it is recommended to choose the public ground transportation method other than air travel. For the case of cars, there are various research discussed shifting from private cars to public ground transportation to enhance environmental sustainability. However, these discussions often overlook the significance of car occupancy and fuel type. Based on the findings of this paper, a car with four passengers of new energy can achieve emissions comparable to those of rail and bus. Conversely, if a car is occupied by just one person, its emissions can surpass those of air travel. Therefore, it is strongly recommended that individuals refrain from traveling alone in cars and consider utilizing renewable energy-powered vehicles. For passengers traveling relatively short distances, bus travel can take as an option to largely reduce emissions compared with car travel (less than four people in a car). And particularly in countries with high emissions from electricity generation, the bus can have lower emissions than the rail.

Rocommendations to transportation companies

While rail travel offers well-to-wheel (WTW) emission savings compared to air travel, it is important to acknowledge that constructing new rail infrastructure requires substantial investments in terms of time and cost. The results of this paper are not to advocate for the construction of new high-speed rail (HSR) lines within the EU, as the life cycle assessment (LCA) impact of rail infrastructure remains a subject of controversy. In order to compete with air travel and car travel, the public ground transportation company can focus on improving travel frequency, lowering the cost, and improving the convenience, comfort, and quality of service. The night trains on existing HSR routes can be attractive to the passengers as it not only demonstrates their sustainability when compared to air travel but also offer cost-saving advantages. For the airline companies, the results have shown that the air network is uncompetitive inside Europe for its density. To reduce emissions and airport congestion, airports can also promote the cooperation of rail/bus with air travel.

Actions to promote a more environmentally sustainable modal choice

The trade-off factor is an important factor to influence the passengers' choice of travel method. With more passengers willing to travel for a longer time to save emissions, the overall transport emission inside EU can be largely reduced. To promote environmental awareness and encourage sustainable choices, it is crucial to provide passengers with clear information regarding the impact of their choices on the environment. Andersson et al.[37] found that there are three types of messages that can improve passengers towards the benefit of less greenhouse gas emissions. The first is to indicate to passengers how the exact amount of greenhouse gas can be saved by choosing a greener transportation method. Most of the current websites already now include that messages. However, the research finds it is only effective for people with high environmental concerns, for other groups of people, another normative message is important to change their decision. For example, 1 tonne of greenhouse gas is equal to 70 trips from Amsterdam – Paris with the Thalys, while only 2,5 economy flights from Amsterdam to Rome. The quantification of the number makes passengers more aware of their decision consequences. In conclusion, by enhancing the transparency of the environmental consequences associated with various transportation alternatives, passengers have the potential to contribute significantly to overall environmental sustainability through their choices of greener transportation options.

V. Conclusion

This paper presented a fully open travel route mapping and emission model for aircraft, rail, bus, and car. The Open Aircraft Model (OpenAP) is utilized for aircraft emission calculation and the ground transportation information is based on General Transit Feed Specification (GTFS) database. The study chooses 810 routes between 41 city centers within EU-27 during March 2023, with a maximum travel time limit of 800 minutes for all transportation modes. The transportation methods are discussed with different occupancy scenarios and fuel type assumptions. The following key findings are summarized:

1) Among all public transport, rail is the most competitive one to replace air travel by offering passengers similar travel time and reducing emissions. However, the role of cars and buses should also not be ignored when considering substituting air travel to save emissions. They can serve to supplement the routes where rail connectivity is limited or absent. Bus emissions remain lower than air travel across all routes, while car emissions significantly depend on occupancy and fuel type. Hybrid Electric Vehicles (HEV), Battery Electric Vehicles (BEV), and Plug-in Hybrid Electric Vehicles (PHEV) with four passengers display similar emissions to rail travel. Conversely, petrol/diesel cars with less than two passengers could emit much more greenhouse gases (GHG) compared to air travel.
2) The results demonstrate that shifting from air to ground transportation can significantly reduce greenhouse gas emissions. The extent of GHG reduction depends on the percentage of passenger shift and their willingness to accept longer travel times to achieve emission reductions. 5 million tonnes of air travel GHG emissions during 2022 can be saved by 100% air passengers choosing the most sustainable ground transportation regardless of travel time considerations among the routes discussed in this paper. 2,53 million tonnes of GHG emission can be saved if 100% passengers are willing to travel 1.2 minutes longer for 1 kg emission saving.
3) The air travel network inside Europe now presents significantly higher density than other ground transportation methods. Even when all the passengers choose the most environmentally friendly way of traveling, there are still 341 out of a total of 820 routes has to be traveled by air due to its dense and time-advantageous network in EU-27.
4) There are notable disparities in the emission and quality of rail networks across Europe. Countries like France, Spain, and Italy have well-developed high-speed rail (HSR) networks with average speeds exceeding 150 km/h. In Germany, while major cities are connected by Intercity Express, the HSR speed falls below 150 km/h, which is lower than the high-quality countries mentioned above. Many Eastern European countries have very limited rail connectivity, making it impractical to replace air travel with rail in these regions. For emissions, rail shows significantly low emissions in Sweden, and France because they use a higher proportion of nuclear and renewable power to generate electricity in these countries. While rail emission is much higher in countries like Germany, and Poland, which means still highly relies on solid fossil fuels to generate electricity.

One significant limitation of this study is the availability and completeness of GTFS data. The model's precision and completeness could be further enhanced if more transportation agencies publicly upload their GTFS data. Additionally, future studies should incorporate factors such as travel cost and time reliability into the model, as these are important considerations for passenger decision-making alongside emissions and travel time. Overall, this paper develops an effective open model to help passengers choose the most sustainable way of traveling without deteriorating their travel time.

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Appendix A

Steps of finding trip with no more than two transfers in GTFS

Step number	Method	Data file
1	Search all the service_id that the expected calculation date is within its start and end running date range	calendar.txt
2	Add or delete the service_id due to exceptions added or removed in our calculation data	calendar_dates.txt
3	Search all the trip_id for the resulting service_id	trips.txt
4	Delete the trip_id in stop_times.txt that does not exist in the result from Step 3 (which means it does not run on the expected calculation date)	stop_times.txt
5	Locate the origin and destination city coordinates	Geocode
6	Query all the stop_id of the stops within 5km from the city center	stops.txt
7	Search all the trip_id for the origin/destination stop_id	stop_times.txt from Step 4
8	Search all the stop_id for the trip_id	stop_times.txt from Step 4
9	Find all the stop_id within a 100m range of the stop_id result from Step 8	stops.txt
10	Search all the trip_id for the stop_id result from Step 9	stop_times.txt from Step 4
11	Match the trip_id and restrict the transfer minutes	
12	Query the route information for the matched trips	routes.txt

Appendix B

Airport Details

Airport Code	City Name	Country	Airport Name
LEMD	Madrid	Spain	Adolfo Suarez Madrid-Barajas Airport
LEBL	Barcelona	Spain	Barcelona/El Prat Airport
EDDF	Frankfurt	Germany	Frankfurt/Main Airport
LFPG	Paris	France	Paris-Charles de Gaulle Airport
EHAM	Amsterdam	Netherlands	Amsterdam/Schiphol Airport
EDDM	Munich	Germany	Muenchen Airport
LIRF	Rome	Italy	Roma/Fiumicino Airport
LFPO	Paris	France	Paris-Orly Airport
LPPT	Lisbon	Portugal	Lisboa Airport
LOWW	Vienna	Austria	Wien-Schwechat Airport
EKCH	Copenhagen	Denmark	Kobenhavn/Kastrup Airport
EDDB	Berlin	Germany	Berlin-Brandenburg Airport
LGAV	Athens	Greece	Athinai/Eleftherios Venizelos Airport
LIMC	Milan	Italy	Milano/Malpensa Airport
ESSA	Stockholm	Sweden	Stockholm/Arlanda Airport
EBBR	Brussels	Belgium	Brussels Airport
EDDL	Dusseldorf	Germany	Duesseldorf Airport
EFHK	Helsinki	Finland	Helsinki/Vantaa Airport
EDDH	Hamburg	Germany	Hamburg Airport
LEMG	Malaga	Spain	Malaga/Costa del Sol Airport
LIME	Milan	Italy	Bergamo/Orio al Serio Airport
LIML	Milan	Italy	Milano/Linate Airport
EPWA	Warsaw	Poland	Warszawa/Chopina Airport
LROP	Bucharest	Romania	Bucuresti/Henri Coanda Airport
LPPR	Porto	Portugal	Porto Airport
LKPR	Prague	Czech Republic	Praha/Ruzyne Airport
LFMN	Nice	France	Nice-Cote d’Azur Airport
LHBP	Budapest	Hungary	Budapest/Liszt Ferenc International Airport
EDDS	Stuttgart	Germany	Stuttgart Airport
EDDK	Koeln	Germany	Koeln/Bonn Airport
LIRN	Naples	Italy	Napoli/Capodichino Airport
ELLX	Luxembourg	Luxembourg	Luxembourg Airport
LBSF	Sofia	Bulgaria	Sofia Airport
LFLL	Lyon	France	Lyon Saint-Exupery Airport

Continued on next page

Table 7 – continued from previous page

Airport Code	City Name	Country	Airport Name
LFBO	Toulouse	France	Toulouse/Blagnac Airport
LEAL	Alicante	Spain	Alicante Airport
LFML	Marseille	France	Marseille-Provence Airport
LEVC	Valencia	Spain	Valencia Airport
LIPZ	Venice	Italy	Venezia/Tessera Airport
LIPE	Bologna	Italy	Bologna/Borgo Panigale Airport
LFBD	Bordeaux	France	Bordeaux-Merignac Airport
LEZL	Sevilla	Spain	Sevilla Airport
LEBB	Bilbao	Spain	Bilbao Airport
LFRS	Nantes	France	Nantes Atlantique Airport

II Preliminary Report (Previously graded for AE4020)

1 Introduction

The European Union (EU) is the world's third-largest emitter of greenhouse gases and has a crucial role in limiting global warming to 1.5°C as the target of the Paris Climate Agreement. The European Green Deal includes the objective of achieving a 90% reduction in transport-related greenhouse gas(GHG) emissions by 2050. However, between 1990 and 2019, the emissions of transport inside EU-27 have risen by 33%, even as other sectors have reduced emissions by 34% [1]. In 2019, the transport sector accounted for 26% of total greenhouse gas emissions in EU-27 [2].In order to reach the European Green Deal goal, it is important to develop approaches to reduce transportation emissions.

Research has shown that one way to reduce overall transportation emissions could be through a modal shift to choose a more environmental-friendly transportation method on a certain route. When looking at emissions of the different transportation types, current aviation operations rely heavily on fossil fuels. It remains one of the least energy-efficient transportation methods nowadays, and aviation emission is forecast to have the largest increases up to 2030. Compared with aircraft, ground transport is rapidly adopting more sustainable energy sources. The road sector's emission is expected to decrease to around 67% as the percentage of petrol /diesel cars will continue to decrease in the following years. Rail is the most energy-efficient mode of passenger transport nowadays. Train travel only accounts for less than 1% of total transportation emissions and is expected not to increase in the future 30 years[2].

There are already research showing that rail always emits less GHG gas than aircraft and shifting aircraft travel to land-based transportation modes can reduce emissions on a large scale. However, the modal shift could only be seen as feasible if the substitution modes could offer similar travel times and costs. According to Follmer et al. [3], aviation plays a minor role over lengths of less than 500 km but becomes the predominant means of transportation over distances of more than 1000 km. Most of the research focuses on shifting short-to-medium distance air travel to HSR, which emits significantly less CO_2 and is time compatible with aircraft[4]. However, there are around 96% percent lengths of routes in Europe where the HSR is not equipped. And building a new HSR infrastructure emits much more GHG compared with conventional trains. For NHSR, Baumeister [5] studied 16 city pairs inside Finland. Substituting air travel with NHSR results in a 95% reduction in emissions, and NHSR could remain time competitive against air travel on distances up to 400 km.

The objective of this research is to utilize multiple open-source models and databases to create a model for estimating and comparing the emissions, time, cost, and frequency of various transportation modes, including aircraft, trains, buses, and cars. The outcome of this study will help passengers in selecting a more environmentally sustainable travel option within Europe. Rather than concentrating on a single train category, this study analyzes the substitution of short-to-medium haul flights with current railway systems, incorporating both high-speed rail (HSR) and conventional trains based on specific routes. Furthermore, the research investigates the advantage of bus and rail collaboration as a transportation mode.

This preliminary report provides an overview of research done so far and introduces the research method. Additionally, the preliminary result is also discussed. A literature review is conducted in Chapter 2. The topics cover current transportation networks inside Europe, their sustainability effects, and modal shift or integration effects. Chapter 4 outlines the methodology employed to address the research topic, including the usage of open data sources and models. Chapter 5 analyzes the current preliminary result of the ten pairs route simulation. The preliminary result contains the time and WTW emission comparison between the transport methods. Chapter 6 highlights the planning to solve the unanswered questions. Finally, in Chapter 7, the conclusion of this preliminary report is presented.

2
Literature Review

The background of the transport network in EU-27 is introduced first. This is followed by Section 2.2, in which the environmental effect is discussed by the transport sector. In Section 2.3, an overview of the literature about the cooperation and competition effects between air transport and ground transport is presented. Previous research has studied the cooperation and competition influence in several aspects, including environmental, time, cost, and passenger demand. It is summarized in Section 2.3 and provides insight for this paper.Lastly, in Section 2.4, the research gap points out what this paper will conduct to supplement the insufficiently discussed topic in the previous work.

2.1. The transportation network in the EU-27

The multi-modal passenger transportation systems comprise of aircraft, cars, rail transit, and buses. The volume of passenger flow within the EU-27, as well as its future growth, varies significantly by the modes and also differs widely across countries. The transportation network is a crucial factor that affects the convenience and feasibility of passenger travel. These circumstances are explained in detail as follows.

2.1.1. Rail transport in EU-27

Between 2015 and 2019, the demand for rail passenger transportation within the EU has a consistent rise, leading to an overall growth of 10.2%, with the highest demand of 420.9 billion passenger-kilometers (pkm) being reported in 2019 [6]. While there was a significant decline in demand in 2020 due to the COVID-19 pandemic, rail passenger transport in the EU has been showing signs of a partial recovery in 2021, with an increase of 16.5% over the previous year, as depicted in Figure 2.1.

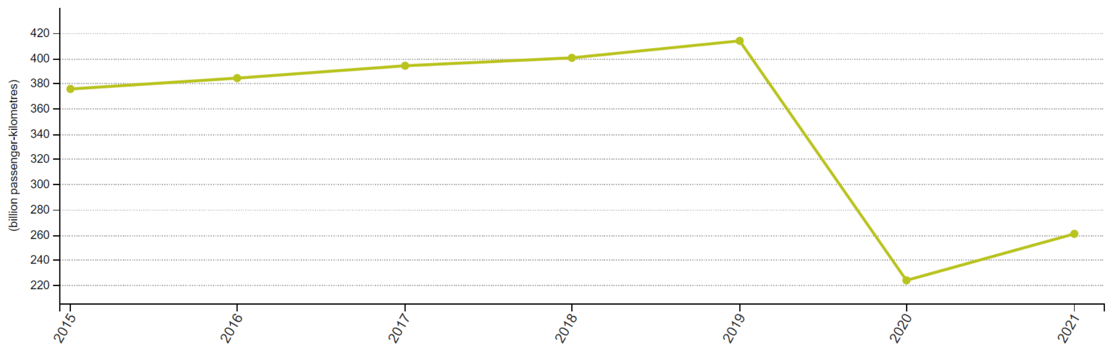


Figure 2.1: Rail passenger transport for main undertakings, EU, 2015-2021 by Eurostat [6]

France and Germany were the largest contributors to the EU rail passenger transport performance in 2021, followed by Italy and Spain as shown in Figure 2.2. These four nations accounted for 68% of the total pkm within the EU-27, amounting to 281 billion pkm in 2019.

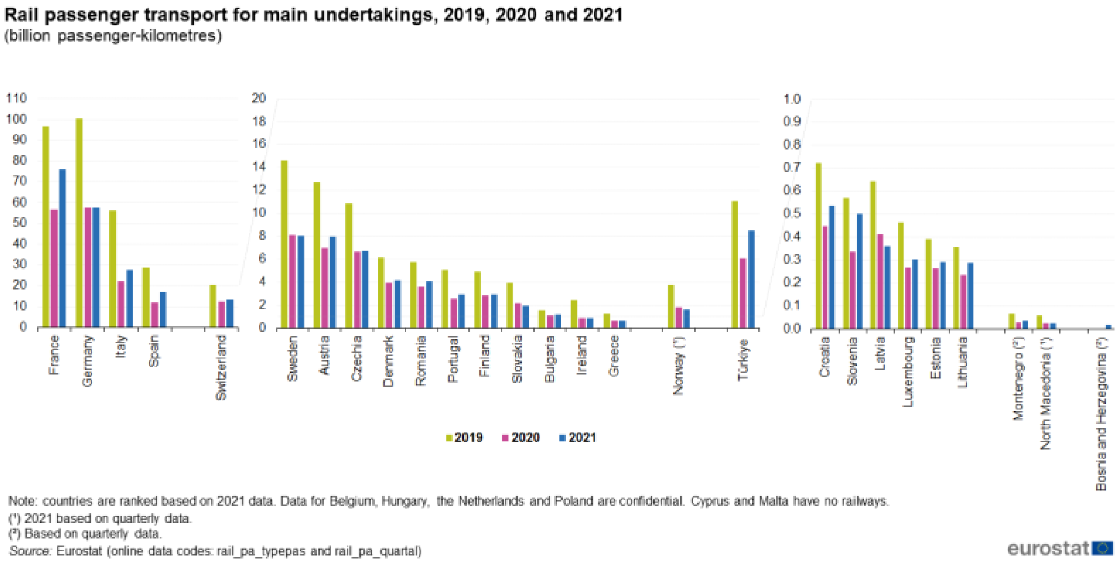


Figure 2.2: Rail passenger transport for countries EU, 2019-2021 by Eurostat [7]

Nowadays, the overall railway length of the EU-27 is around 200,099 km, but there are considerable disparities across the EU[1]. Germany, France, Poland, Italy, and Spain are the five EU-27 countries with the longest rail network systems, with Germany leading at 37,976 km of track and France following closely with 29,273 km. However, the Southeastern countries in Europe are facing a slow railway line development. As of 2021, countries such as Croatia and Serbia possess only 10% of the total rail length of Germany. The development of new rail lines in the EU today is driven by high speed rail (HSR) projects; high-speed lines are now led by Germany, Spain, France, Finland, and Italy as in Figure 2.3. At the main segment, trains on high-speed lines can reach up to 321 km/h as shown in Figure 2.4. The length of the HSR lines in the EU□27 increased from 1001 km in 1990 to 11526 km in 2020[1]. By 2030 the planned high-speed are extended to over 30,000 Km.

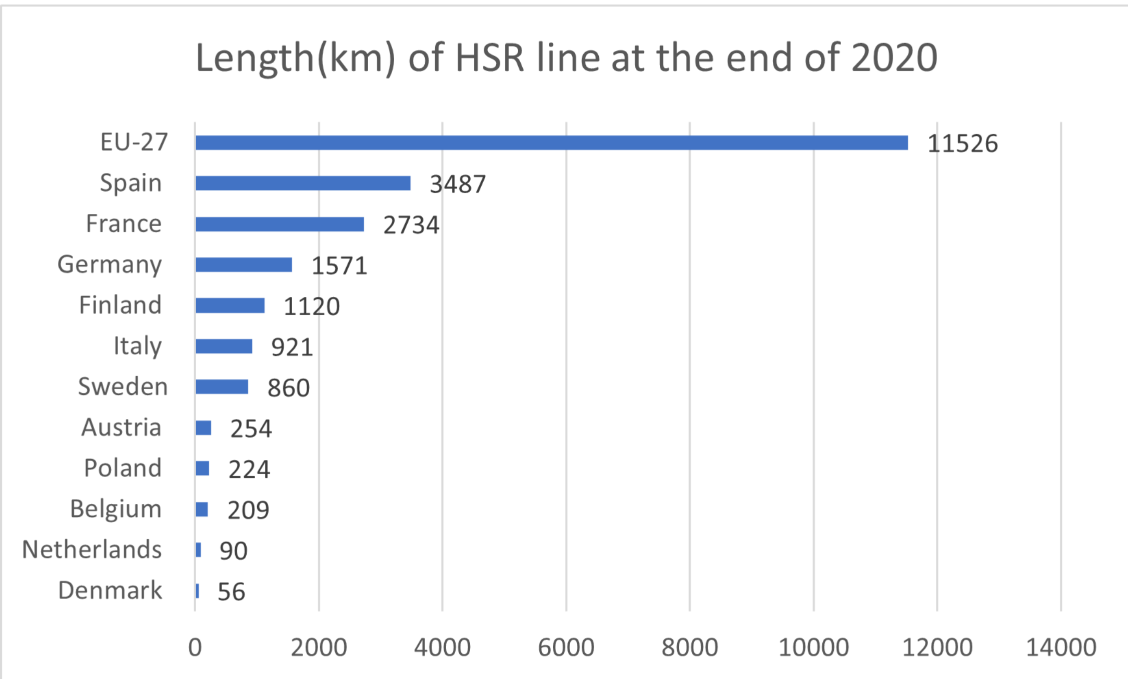


Figure 2.3: HSR length by country in EU-27 in 2020

Figure 2.4: Rail network in Europe by Wikipedia[8]

Inside EU-27, Spain nowadays has the longest HSR line of 4447km in use, with long-term plans to expand it up to 7,000 km. Much research has demonstrated that Within rail services, high-speed railways (HSR) represent the most competitive transport mode which can actually compete with air transport in terms of time[9]. Many airports, such as Schiphol, Frankfurt Main already connected with the HSR, and the HSR plays the role of competing or cooperating with aircraft. Passenger-km by HSR in the EU-27 has grown by 283 % since 1995, with a total of 126 billion passenger-km in 2018. Furthermore, there has been a growing share of HSR in rail travel, increasing from 17.3% in 2000 to 31% in 2018[10].

2.1.2. Air transport in EU-27

In 2021, the total number of passengers traveling by air in the EU was 373 million [7], a substantial increase of 35% compared with 2020. Compared with the pre-pandemic year of 2019, the number of passengers in air transport decreased by 64%, indicating that recovery was still far away. The passenger kilometer (pkm) of air has the sharpest increase among all the transport methods as in Figure 2.5. The air transport pkm is the second largest in the EU-27 in 2019, only after the private car.

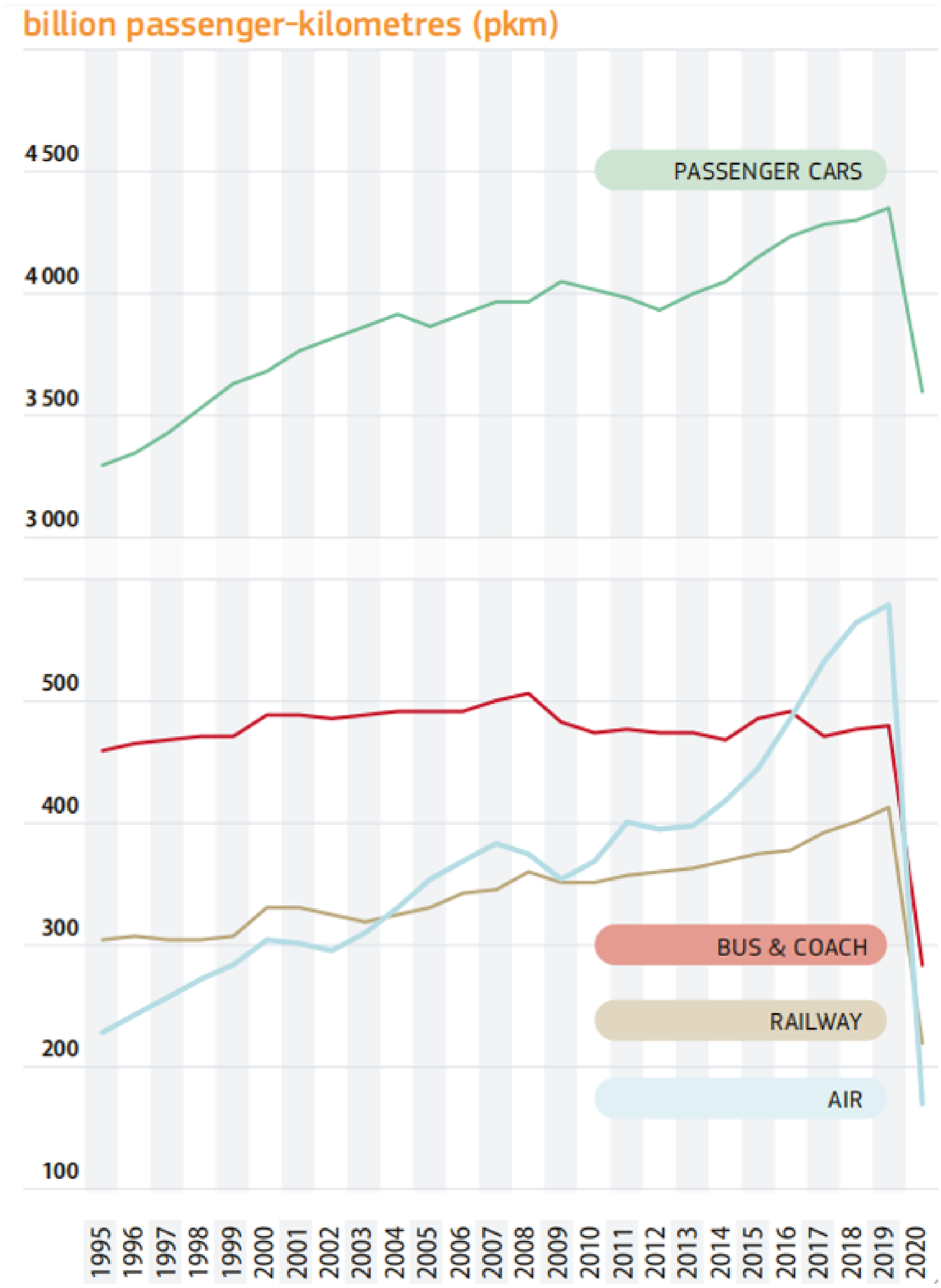
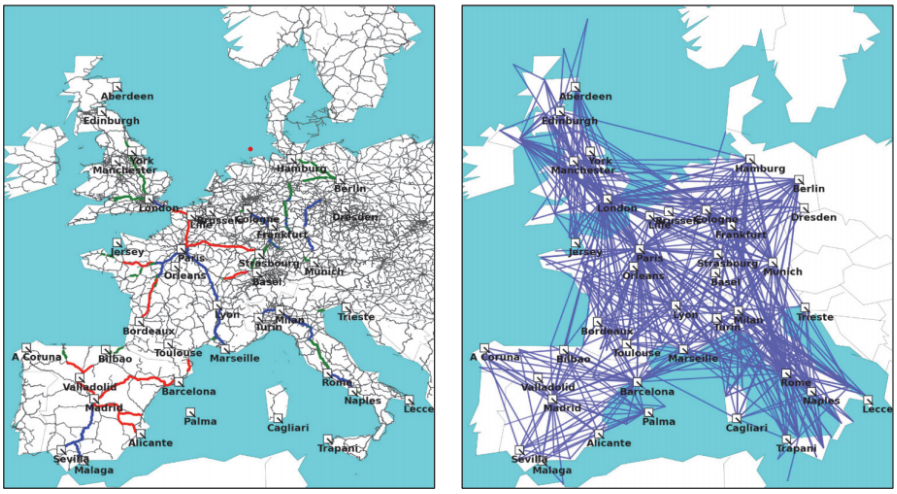


Figure 2.5: EU-27 Performance for passenger transport 1995-2020 – BY MODE by European Commission[1]

Intra-EU and domestic transport represented 60.8 % of the total air passenger transport in 2021. [11]. Most of the intra-EU and domestic flights are short-haul flights. According to Grimme and Jung [12], short-haul flights produce more than twice as much CO2 emissions per kilometer than long-haul flights. This is due to the energy-intensive take-off and climb phase being distributed over a shorter flight distance compared to medium- and long-haul flights. Short-haul flights are also the ones that could be replaced the most easily by other modes of transportation, due to relatively shorter distances.

According to Dobruszkes [13], the expansion of air service in Europe has outpaced that of HSR. The network in Europe of air service is highly developed and far denser than the HSR network. In 2010, only 264 city pairs had HSR routes of 3 hours or less, compared to 3,262 city pairs that were connected by air links, shown in Figure 2.6. There is a market segment where there are no high-speed trains, or those that do exist are unable to compete with planes.



(a) HSR network (data source: OpenStreetMap)

(b) Airport network (data source: Sabre Airline Solutions)

Figure 2.6: Rail network and air network comparison in Europe[13]

2.1.3. Passenger Car and bus in EU-27

The car offers the advantage of flexibility, as it can accommodate passengers' time and reach destinations where public transport is not possible. In Europe, car transport dominates passenger kilometers, accounting for about 71.7% of the estimated total pkm traveled in 2019 [1], as shown in Figure 2.7. 8% of the pkm in 2019 is from the bus and coach. Traveling by bus is often the most cost-effective option in Europe. Buses have the advantage of access to smaller locations that the train or plane network does not reach. Particularly in countries such as France and Spain, the bus network is highly developed. The bus can feed passengers from smaller locations to the main airport hub or train station. With many companies such as Flixbus, and BlaBlacar now offering intercontinental routes, buses have also become a viable option for traveling across countries.

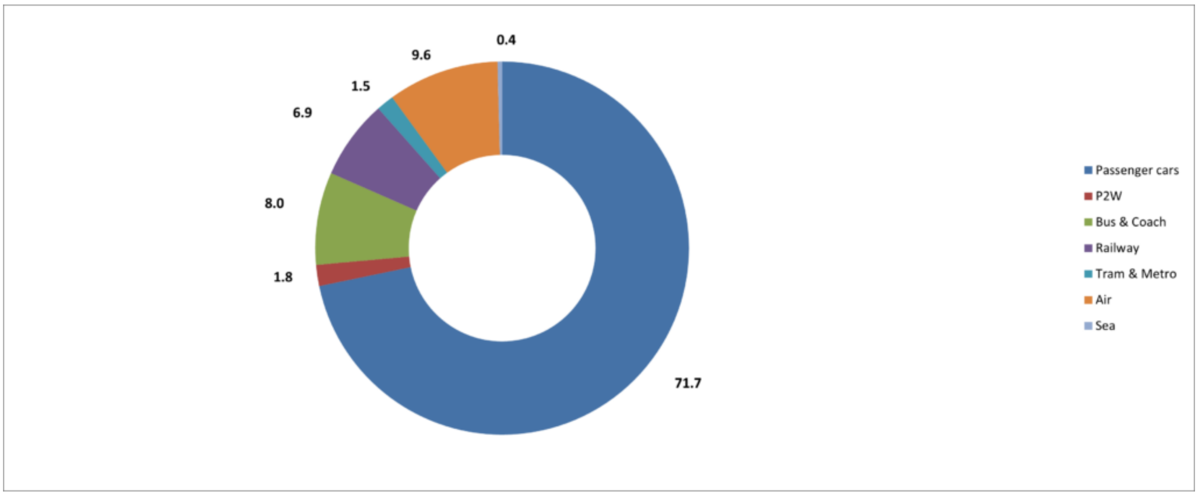


Figure 2.7: Passenger transport modal split in EU 27, 2019

2.2. The transportation environmental impact

2.2.1. Scope of the emission

The different scope of the emission is illustrated in Figure 2.8.

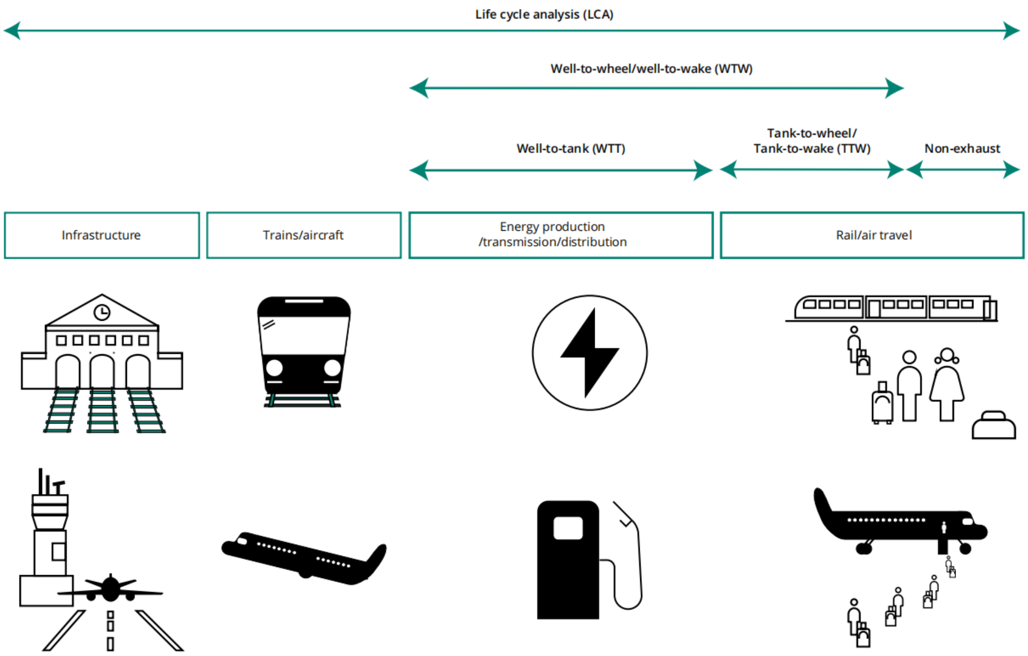


Figure 2.8: Conceptual illustration of the scope of environmental cost calculations by European Environment Agency [14]

Within the WTW scope, an electric train/car does not have Tank-to-Wheel (TTW) emission, since it does not generate direct emissions. Its Well-to-Tank (WTT) emissions are from electricity production/-transition and distribution. Conversely, for fuel-powered transport methods, have direct CO_2 emissions from fuel burning. And the WTT emissions from these fuel-powered transports are generated during the production and transportation of fuel. By comparing the WTW emissions from the energy required to propel the vehicle, HSR appears to be more efficient than air travel, according to the International Union of Railways [15]. However, the CO_2 emissions in the WTW scope are not the only impact of the rail sector. The indirect emissions caused by the maintenance and construction of train infrastructure should also be included in the LCA analysis. The construction of the new rail infrastructure produces far more emissions than the airport infrastructure. In addition, the effect on landscape, townscape, biodiversity, and history should also be considered [16].

- **well-to-tank (WTT):** take place during the production, transmission and distribution of the energy used by trains and aircraft
- **tank-to-wheel emissions (TTW):** exhaust emissions that take place during the operation of the train or aircraft
- **well-to-wheel/well-to-wake (WTW):** considers both WTT and TTW emission
- **life cycle analysis (LCA) :** also consider energy and emissions involved in the construction and maintenance of the infrastructure, the manufacturing of the vehicles and end-of-life aspects

2.2.2. Air travel emission

In 2019, all departing flights from Europe were accountable for 13.4% of GHG emissions from the transport sector, making aviation the third largest source of emissions in the transport sector after road, navigation, as depicted in Figure 2.9. Aviation emission increases 44% from 2000 to 2019, which is far high other transport as in Figure 2.10. Furthermore, aviation emission is projected to grow til 2040. It shows that air traffic growth outpaces fuel efficiency improvements.

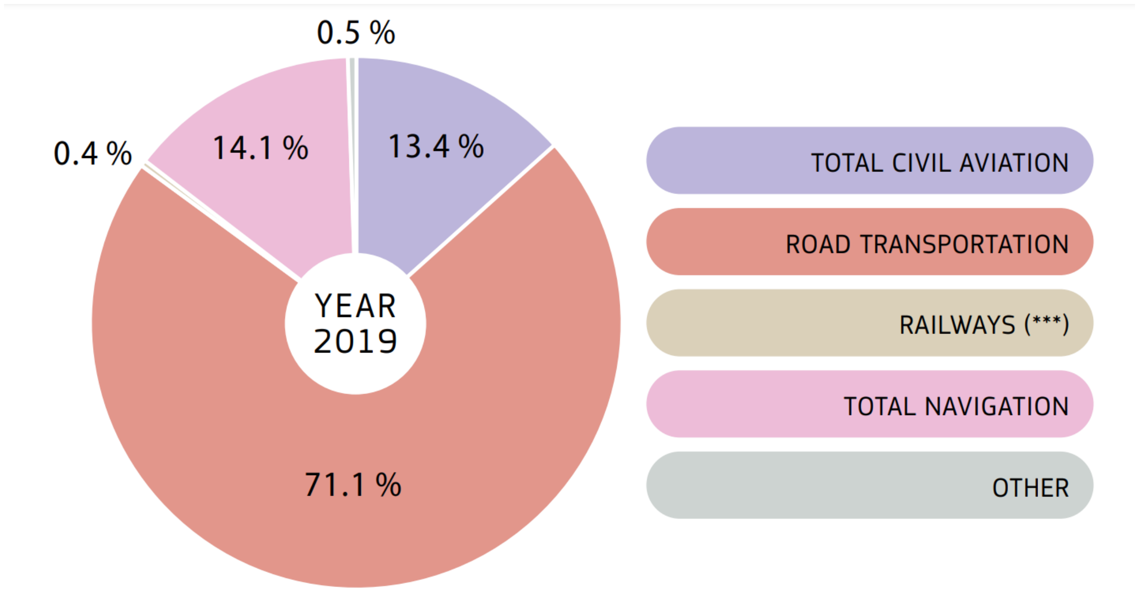


Figure 2.9: SHARE OF TRANSPORT GREENHOUSE GAS EMISSIONS IN EU-27 IN 2019 by European Commission [1]

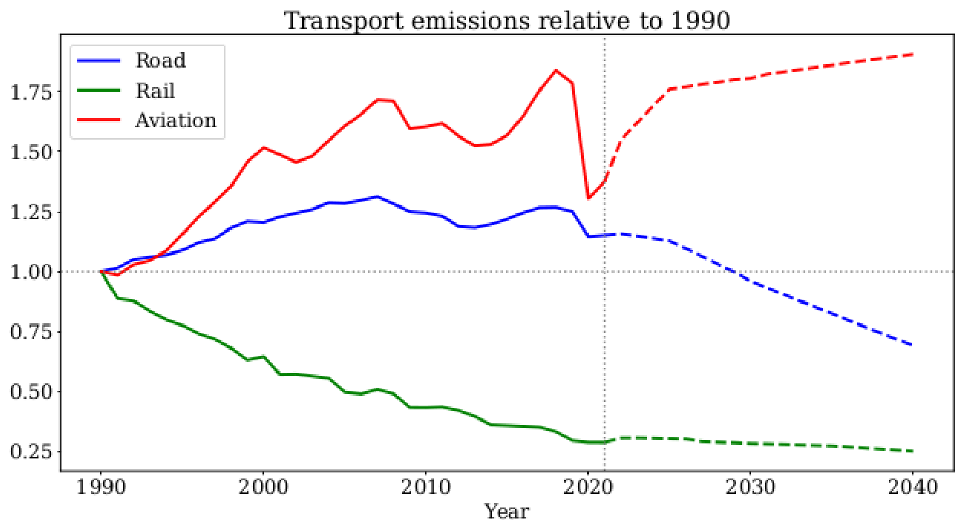


Figure 2.10: Passenger transport emission growth by mode in EU 27 by EEA [2]

Among the flights, short-to-medium haul flights fall the distance under 1500km, occupying 25.4% percentage of emission [11]. The short-to-medium haul flights produce the highest amount of GHG emissions per kilometer, even though longer flights mean more emissions in absolute terms and have a higher percentage of the total emission.

2.2.3. Car and bus emission

In the total transport emission, road transport accounts for 71.1% percentage, far over other sectors. Among road transport, cars are the main emission factor, accounting for 60.6% emission of ground transportation. As in Figure 2.12, the car has the second largest CO_2 emission pkm, only after passenger flights. Therefore, it is also a widely discussed topic about model shifting from private cars to bus, rail. However, only road transport emissions are projected to decrease until 2030, due to the introduction of new car CO_2 emission standards. The 95 g/km emission target for cars applies from 2021. As in Figure 2.13, the energy consumption per car passenger kilometer decreased and in 2019 it was 6.3% lower than in 2000.

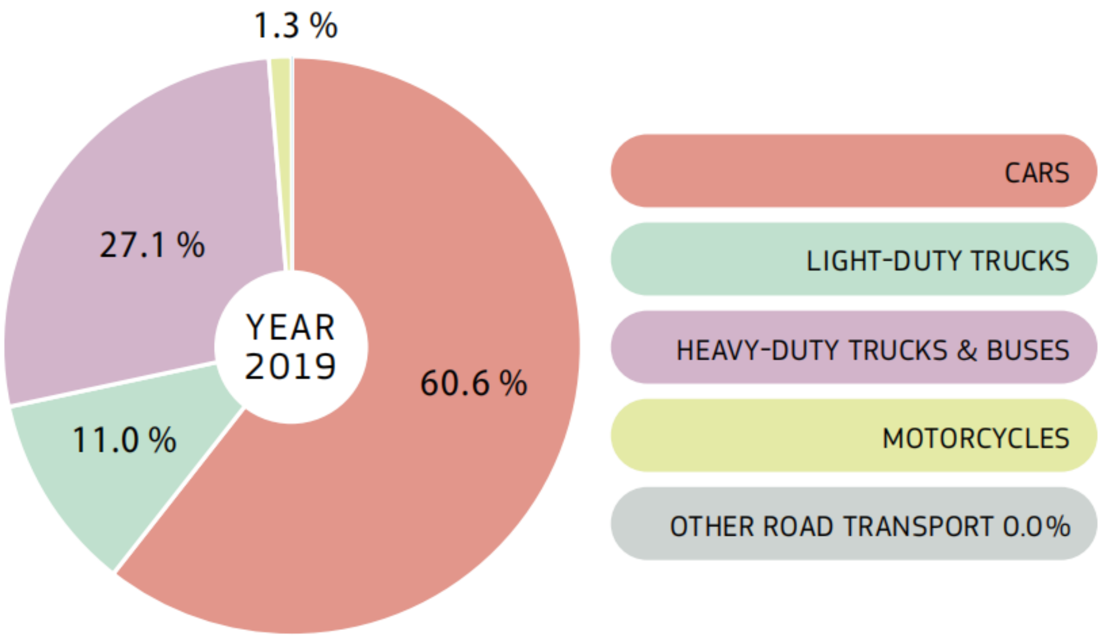


Figure 2.11: Car and bus emission percentage [1]

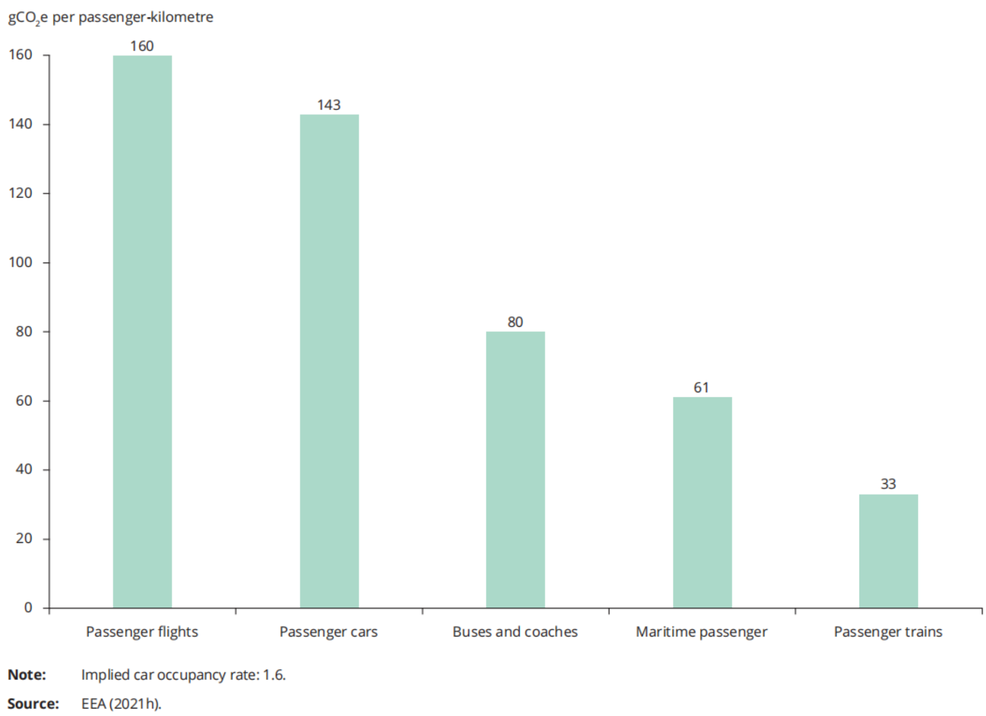


Figure 2.12: Average GHG emissions (gCO2e per passenger-km), well-to-wheel, for passenger transport in the EU-27, 2018 by EEA [17]

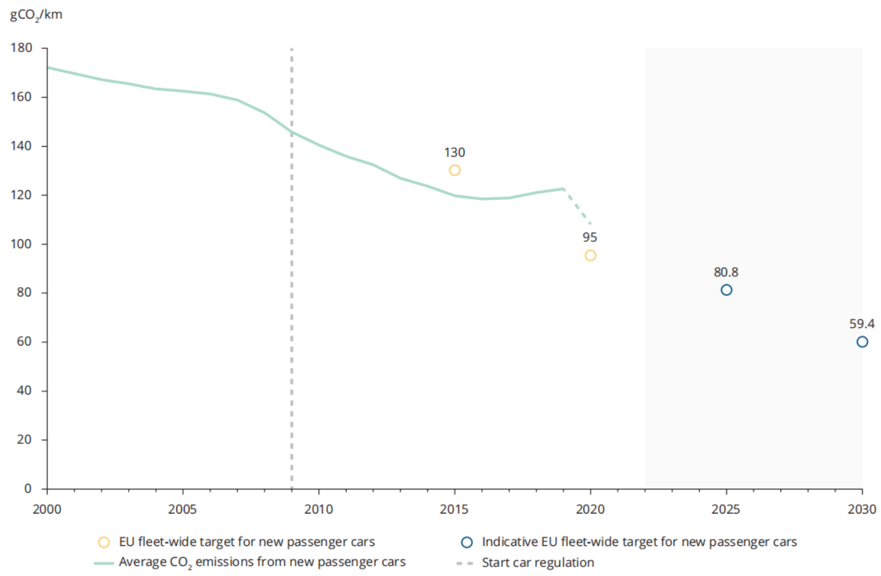


Figure 2.13: Average CO2 emissions per kilometre (NEDC) for new passenger cars, 2000-2030 by EEA [18]

The alternative powered technology for bus and car include battery/hybrid electricity and alternative-fueled. Overall in 2021, 68.8% of all new buses registered in the European Union still ran on diesel, while all alternatively-powered vehicles made up the remaining 31.2% of the EU bus market in 2021. The market share of the new diesel bus decreased from 89.8% in 2018 to 68.8% in 2021. In the case of cars, alternatively-powered vehicles experienced significant growth, increasing their market share from 7.7% in 2018 to 40.4% in 2021. Diesel-powered accounted for 19.6% of the new cars, and petrol-powered vehicles made up 40% of the new car market in 2021. Of the alternative options, hybrid electric cars experienced the most significant growth, with their market share rising from 4% to 19.6% in the past three years. The road sector decarbonises faster than other transport modes. According to the Commission proposal [19], all new cars and buses registered from 2035 have to be zero emissions. The emission from the road sector will have a further reduction.

2.2.4. Rail emission

For the rail sector in Europe, there are mainly two options related to the type of energy used: diesel engines and electrical units. Regarding main lines, 60% of the European rail network is already electrified and 80% of traffic is running on these lines [20]. Among the transport section, rail accounts for 0.4% of those GHG emissions. EEA [2] states that the passenger rail has the best environmental performance among the transports method in the EU, with GHG emissions per pkm that are only a fraction of most other modes as shown in Figure 2.12. During the infrastructure construction phase, which involves building tracks and stations, the HSR industry produces a considerably higher amount of GHG compared to the road sector due to the need for specialized infrastructure. However, road transportation emits several times more CO_2 per passenger during operations, but it doesn't require extensive infrastructure construction.

2.3. Competition and Cooperation Effects between Air Transport and ground transport

Besides improving the transport method itself energy efficiency, two other methods have been investigated before and demonstrated a positive effect on the environmental aspect. The first one is the modal shift, referring to the strategy of shifting the entire trip from unsustainable transport to a more environmentally friendly transport method. The other one is modal cooperation where several transport providers work together to provide transportation services, in other words, substituting part of the trip with a more sustainable way of travel. The modal shift and cooperation only work out when it provides a similar or better travel experience to the passengers. The main factors determining the passenger choice are price, travel time, travel time reliability, frequency of the connections and other factors such as convenience, comfort, and safety [21]. Each transportation mode has its own unique operational and commercial advantages and properties. These modes can either compete or supplement each other in various aspects including cost, speed, accessibility, frequency, and comfort.

This section gives an overview of the model shift and cooperation effects between air transport and ground networks as reported in the previous study.

2.3.1. The modal shift

Replacing short-haul flights with high-speed rail (HSR) has been widely discussed as one solution to mitigate the climate change impacts of aviation. A considerable body of work has been published regarding potential CO_2 reductions that can be achieved by replacing at least a portion of air travel with high-speed rail (HSR). But for a valid model substitution, not only emissions, travel quality should also be considered.

Sun et al. [22] consider a preferable range for HSR between 200 km and 1,000 km. The substitution range can enlarge it up to 2000 km with the option of high-speed night trains.

Chiara et al. [9] considered four Italian routes for HST from a specific energy point of view. The result shows for a trip of distance 800km or even up to 1000km, HSTs appear to be a viable option that would allow the sustainable development of transportation systems.

EEA [14] analyses 20 city pairs up to 1100km inside the EU and consider environmental cost including WTW emission, noise, air pollution, and non-CO2 effects. The result shows that the environmental costs of rail travel are substantially lower than those of air travel.

Andrew Miller[23] uses the flight emission data from ICAO to study 8 city pairs in the North USA, the result shows rail travel has generally lower CO2 emissions than air travel. But the result is related with the distance, powertype of train and aircraft type. The emissions for electrified rail emission is substantially lower than air. At flight distances of over 700 miles, air travel using single-aisle jets can have lower per-passenger CO2 emissions compared to diesel-powered rail travel.

While HSR can certainly deliver substantial gains in travel time, building the necessary infrastructure requires a significant amount of funding as well as time and might even have negative outcomes on climate change and local biodiversity [24]

Jones [25] studied the total life cycle environmental impact of the planned high-speed rail line from Lisbon to Porto, Portugal. The result shows that 31 % of the total impact of CO_2 is ignored because the impact from construction, maintenance, and end-of-life is not included.

For short-haul flights, even other land-based transport modes, such as traditional trains and long-distance buses, are considered suitable alternatives and contribute to operating greener trips. Stefan Baumeister [26] all 16 city pairs in Finland for which short-haul flights are offered with existing NHSR based on the total carbon dioxide equivalent emissions (CO2-eq) and real travel times from door-to-door. A 95% reduction of emissions will happen in Finland if replacing all short-haul flights with NHSR. In terms of travel times, NHSR could remain competitive against air travel on distances up to 400 km.

The passenger car discussion also exists about the replace the private car with the HSR.

Gulcin Dalkic [27] studied two most demanded HSR lines in Turkey, ANK-ESK and ANK-KON. The modal shift from road-based modes to HSR was possible to have the reduction amounts as 24.3 ktCO2/year, excluding the induced demand. He suggests HSR can bring larger induction if new HSR lines can create a network effect along the main corridor and generate high HSR demand that would be shifted from car, and even air, on the longer routes.

Akerman (2011) [28] that High-Speed Rail (HSR) had the potential to attract intercity travelers from the air and private car. The life cycle emissions analysis in Sweden found CO2-equivalents per annum by 2025/2030 can reduce 550,000 tons with 40% from a shift from air and road travel to high-speed rail travel.

Between ground transportation, a lot of studies show by adopting public transport (railway,bus) instead of personal cars, pollutant emissions can be reduced efficiently.

Rojas [29] find that the carbon dioxide was estimated to be reduced by 203,251 t/CO2 emissions per year for shifting from car to other modes of transport (bike and public transport) in Barcelona metropolitan area.

By comparing the energy and emission performance of aircraft, intercity bus, SUVs, and automobiles, Haobing(2016) [30] highlights the fuel efficiency and low emissions per passenger-kilometer of travel (PKT) from intercity buses.

2.3.2. The modal cooperation

Another option would be establishing intermodal passenger transport, which involves using multiple means of transit in a given journey. An example of this would be taking a bus, or rail to the airport hub and taking airplane travel for the rest of the journey. The most studied model cooperation is the air-HSR intermodel.

The recent introduction of the integrated HSR-air option—efficiently coordinating HSR and airlines with measures such as integrated luggage handling services and on-site HSR station at the airport—enables an interconnecting passenger to perform intermodal trips more easily.

Albalate et al [31] find that direct competition between HSR and airlines is still dominant, but they also provide evidence about HSR's feed services to long-haul air markets in hub airports, particularly in those with HSR stations.

Clewlow et al. [32] suggest that HSR might serve as a complementary mode to relieve congestion at airports by providing short-haul services in support of longer-haul airline services

Zanin et al. [33] With HSR, passengers traveling with aircraft and private car are reduced, leading to environmental benefits. Increasing the travel cost of private car is picked up by air transport rather than HSR, leading to negative environmental impacts.

Jiang [34] discovers that air-HSR corporation reduces emissions per passenger on long-haul routes, but not necessarily on short-haul routes where the HSR operator interacts with the airline.

2.3.3. Modal choice determining factors

Specifically for people's modal choice between the transportation method (so for long-distance journeys), KiM [35] found the following ranking of criteria:

- travel time;
- number of travel opportunities per day;
- price;
- comfort (reservation system, travel information before and during traveling, luggage handling, comfort at stations/airports, comfort in train/airplane).
- punctuality

Due to different characteristics and regional aspects, each model of transport has its own competitive distance and area.

2.4. Research gaps

Open source model establishment

Research studies often use the closed-source or hand-collected datasets [22]. This makes it difficult to reproduce the results obtained in the study. Furthermore, this leads to inconsistent views on networks, being taken at different times, with different observable variables.

Among European countries, the number of studies shows disparities between the countries. There is abundant analysis focused on Spain, because of many datasets available for public use provided by HSR operator Renfe in Spain. On the other hand, because of data confidentiality issues, only very limited research on the impact of HSR in Germany has been published[22]. There is a strong need for an open-access multi-modal transportation database. This paper aims to solve this problem by using the GTFS to build an open-source planning model for buses and rail. The users can freely download the up-to-date GTFS. The GTFS is a collection of txt files containing abundant information about railway trips, stops, departure/arrival time, train types, company names, and so on. It enables abundant research on the train route. Furthermore, the users can easily add or modify the parameters in the GTFS file.

Ground transportation

Another notable limitation in the existing research is its predominant focus on replacing air travel with High-Speed Rail (HSR). However, only 4% of European railways are equipped with this technology, which means the reachable place by HSR is very limited. This study aims to address this gap by exploring the potential of integrating both High-Speed Rail (HSR) and Non-High Speed Rail (NHSR), which enlarges the railway reachable range. Additionally, the role of buses and cars has often been neglected in previous studies. Therefore, this research also investigates the extent to which buses and cars could independently replace air travel or complement rail travel as a viable alternative to air transportation.

LCA emission

Most of the previous research focus on the WTW emission comparison. The manufacture, and maintenance emission is not fully discussed. This paper will compare the result of WTW and LCA emissions.

3
Research Questions and Objectives

3.1. Research Questions:

The main research question of this thesis is:

What is the difference in CO_2 emissions attributable to a single passenger choosing a transportation method with existing systems?
Sub-research questions:

- What open data sources can be used for conducting air-ground transport studies?
- How a simplified range-emission model for flights can be constructed?
- What models can be used to estimate emissions from trains, cars, and buses?
- How to model the effects of electrification in ground transportation (electric cars)?
- How to consider the emissions caused by electricity production and transmission?
- How to use the sustainability model to analyze the existing transport data?
- How to analyze the travel time, cost, and frequencies of the transport?
- What model adaptations can we consider for future scenarios?

3.2. Research Objectives

The objective of this master thesis project is to design models that can be used to estimate and compare emissions and the environmental impacts of aircraft and other ground transport modes.

4

Methodology

4.1. Setup

As shown in Figure 4.1, The top 30 busiest airports in Europe ranked by total intra-EU27 passengers in from 2019 to 2021 are chosen as the target [7]. The ranking and passenger flow number for the year 2021 are provided in Table 4.1. In order to provide a geographically balanced collection of city pairs throughout the EU's mainland, three additional airports are added: Sofia Airport in Bulgaria, Luxembourg Airport in Luxembourg, and Thessaloniki Airport in Greece.

Between these 33 airports, total 528 pairs of origin/destination exist, covering the major flight routes inside Europe. After removing the connection in the same city where the flight does not exist, there are a total of 526 links between these 33 airports. The distance between airport pairs is categorized into bands as indicated in Figure 4.2. A total of 430 connections, which is approximately 81%, have a distance below 2000km, which is considered the maximum feasible range for the rail to potentially replace. 30% percent of the route is under the distance of 850km indicated as the most competitive range for HSR according to previous studies.

Figure 4.1: The chosen airports in EU-27

Table 4.1: busiest Airport ranking in EU-27in 2021 by Eurostat[7]

ranking	country	Airport name	Total passengers(thousands)	Intra-EU
1	FR	PARIS-CHARLES DE GAULLE	26,187	13,342
2	NL	AMSTERDAM/SCHIPHOL	25,491	14,292
3	DE	FRANKFURT/MAIN	24,765	13,512
4	ES	ADOLFO SUAREZ MADRID-BARAJAS	23,193	16,670
5	ES	BARCELONA/EL PRAT	18,475	15,751
6	FR	PARIS-ORLY	15,719	13,119
7	EL	ATHINAI/ELEFTHERIOS VENIZELOS	13,356	10,226
8	DE	MUNCHEN	12,474	9,151
9	PT	LISBOA	12,155	8,384
10	IT	ROMA/FIUMICINO	11,586	9,115
11	AT	WIEN-SCHWECHAT	10,466	6,835
12	DE	BERLIN-BRANDENBURG	9,929	6,983
13	IT	MILANO/MALPENSA	9,578	7,217
14	BE	BRUSSELS	9,331	6,051
15	DK	KOBENHAVN/KASTRUP	9,148	6,479
16	ES	MALAGA/COSTA DEL SOL	8,747	6,576
17	IE	DUBLIN	8,262	5,031
18	DE	DÜSSELDORF	7,939	4,833
19	SE	STOCKHOLM/ARLANDA	7,493	5,857
20	PL	WARSZAWA/CHOPINA	7,440	4,258
21	RO	BUCURESTI/HENRI COANDA	6,888	4,847
22	FR	NICE-CÔTE D’AZUR	6,529	5,387
23	IT	BERGAMO/ORIO AL SERIO	6,465	5,546
24	IT	CATANIA/FONTANAROSSA	6,114	5,892
25	ES	ALICANTE	5,813	3,991
26	PT	PORTO	5,787	4,752
27	DE	HAMBURG	5,314	3,852
28	HU	BUDAPEST FERENC INTERNATIONAL	4,590	3,063
29	CZ	PRAHA/RUZYNE	4,370	2,864
30	FI	HELSINKI-VANTAA	4,295	3,330
31	BG	SOFIA	3,245	2,289
32	LU	LUXEMBOURG	2,003	1,766
33	GR	Thessaloniki Airport Makedonia	1,266	nodata

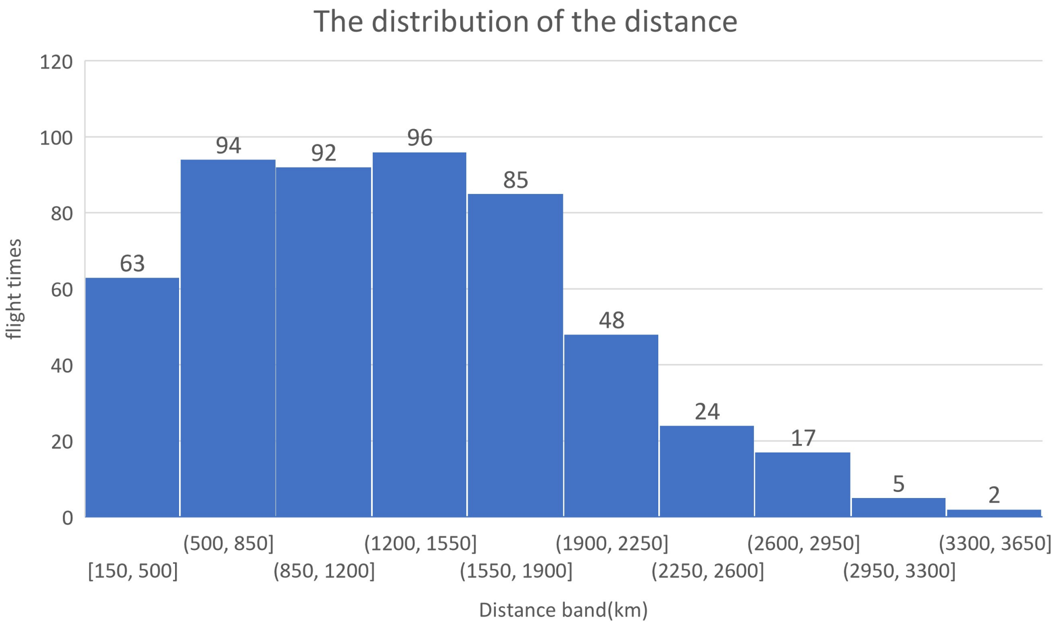


Figure 4.2: The distance distribution

4.2. Route plan

Between the origin and destination, each of the transport options covered in this paper (car, bus, airplane, and train) has unique travel features, such as distance, duration, and the number of stops. In order to compute the emissions accurately, it is crucial to map out the travel itinerary first. The following section discusses the calculation method for each transport method respectively.

Aircraft flight profile

Multiple sources provide flight data, including EUROCONTROL, OPENSKY. However, for this study, crowdsourced air traffic data is utilized, which is extracted and filtered from the complete OpenSky dataset [36]. This database provides a monthly file starting from January 2019, spanning all flights observed by over 2500 members of the network. To reflect the pre-COVID-19 conditions, this study focuses on the data for March, April, and May 2019. By querying the dataset with the origin and destination airport codes, specific information about the aircraft type and travel duration for a given route can be obtained. Additionally, the great circle distance (GCD) between the origin and destination airports is calculated using the following Equation 4.1:

$$\text{hav}(\Theta) = \text{hav}\left(\phi_B - \phi_A\right) + \cos\left(\phi_B\right)\cos\left(\phi_A\right)\text{hav}\left(\lambda_B - \lambda_A\right) \tag{4.1}$$

$$d_{AB} = r \times \text{archav}(\text{har}(\theta)) \tag{4.2}$$

where ϕ_A and λ_A is the origin airports' latitude and longitude. ϕ_B and λ_B is the destination airports' latitude and longitude. The d_{AB} is the GCD distance result.

The subsequent step is fuel estimation through the utilization of Fuel Estimation in Air Transportation (FEAT)[37]. The model of FEAT enables fuel estimation by using origin-destination airport distance and aircraft type as sole inputs. It is illustrated in Section 4.3.

Railway and bus route

To map the travel route of rail and bus, there are already many API available. However, the majority of these APIs may have a limit on the number of active sessions a user can have at any given time and are not free to access. This paper aims to build an open-source rail and bus route planning model, that users can easily download and modify parameters. The journey schedule for the bus and railroad takes advantage of the latest GTFS feed in March 2023. The General Transit Feed Specification (GTFS) is a transport data specification published by public transit agencies. The advantage of GTFS is that the public can free download it and keep updates to the newest schedule, which facilitates follow-up research. A GTFS feed is composed of a series of text files collected in a ZIP file. Each file models a particular aspect of transit information: stops, routes, trips, and other schedule data. The details and connection of each file are defined in Figure 4.3. The following Figure 4.4 shows the steps of using the origin and destination to calculate the route with no more than two transfers in GTFS. The specific steps of searching the direct connection are depicted in Table 4.2. More details in finding the GTFS route are discussed in Chapter 6. The results contain the distance of the trip, travel time, the stops along the trip, and the types of trains.

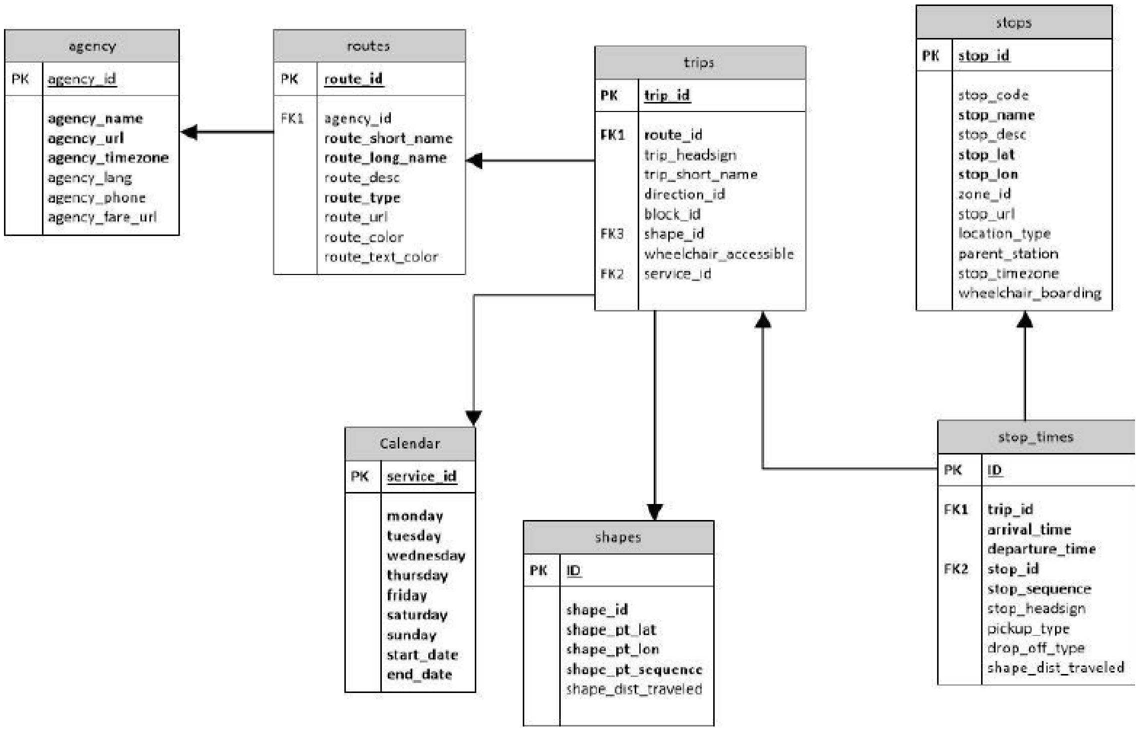


Figure 4.3: The GTFS link by Mishevska [38]

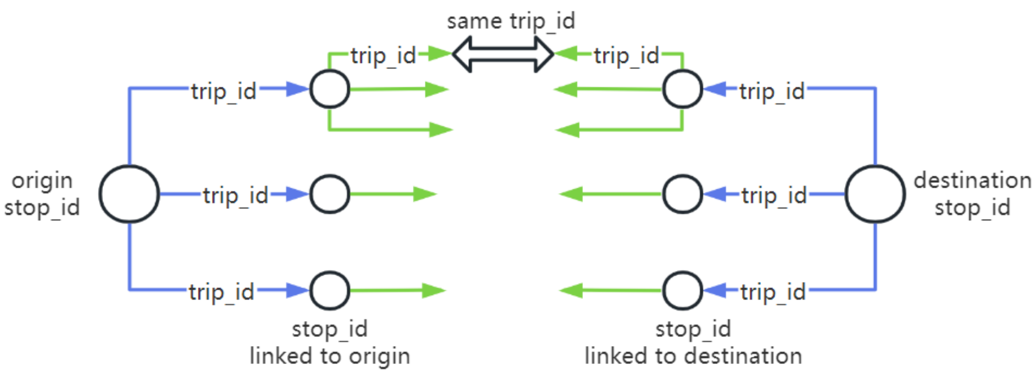


Figure 4.4: The GTFS method

Table 4.2: steps of finding trip with no more than two transfer in GTFS

step number	Method	data file
1	Locate origin and destination airport coordinates	Openap
2	Query all the stop_id of the stops within 5km from the airport	stop.txt
3	Search all trip_id for the origin/destination stop_id	stop_times.txt
4	Match trip_id	
5	Query the route information for the matched trips	routes.txt

This research aims to gather GTFS by European operators. However, the GTFS from some operators is not publicly available. Figure 4.5 shows the availability of the GTFS for the countries in Europe. National-wide feeds covering almost all traffic information are available for Germany, France, Netherlands, Spain, and Belgium. The North European nations, including Sweden, Finland, and Norway, have complete GTFS data as well. However, in many countries in Eastern Europe, complete national wide GTFS data is unavailable. While data for Italy is also incomplete, it includes national-wide GTFS information from TRENITALIA, the country's largest operator. Portugal only has regional GTFS data available for a few cities. For these incomplete GTFS countries, which shows as the yellow and red color in Figure 4.5, the regional transportation information from operators is merged. And their main cross-border travel information is supplemented by Eurail [39], an all-in-one train ticket website with information on most trains across Europe

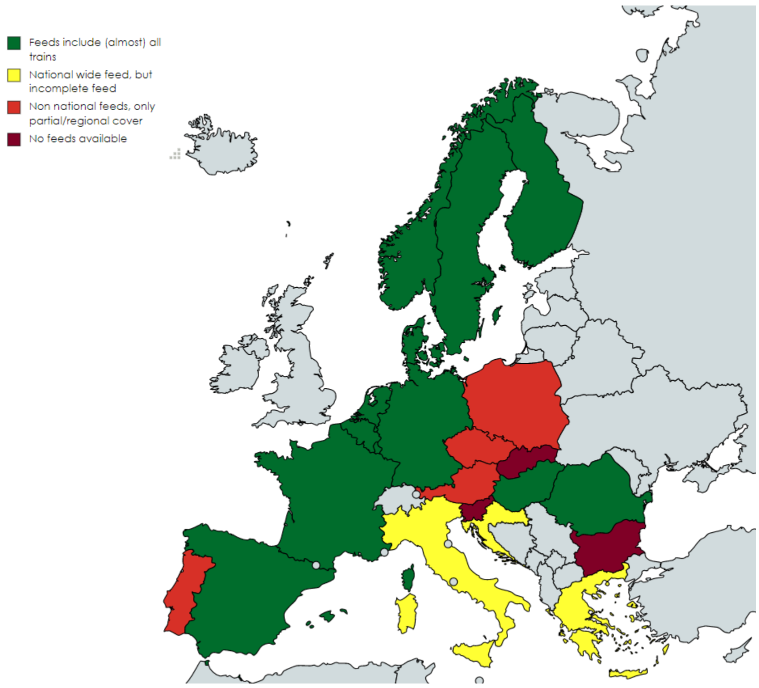


Figure 4.5: The rail GTFS availability inside EU27

For the main long-distance bus company, the availability of data is as followed in 4.3 The Flixbus and BlaBlaBus have the complete up-to-date GTFS data, while data are not available for the Eurolines and Megabus. The Flixbus stop connects almost all the main cities inside Europe as shown in Figure 4.6, which is sufficient for this study.

Table 4.3: Bus GTFS availability

company name	availability
Flixbus	Yes
Eurolines	No
Megabus	No
BlaBlaBus	Yes

Figure 4.6: The Flixbus destination in Europe by Flixbus website[40]

Among some GTFS routes, data regarding the traveled distance is absent. Under that circumstance, rail travel distance can be calculated by summing the straight linear distance between two connected stations along the route. Similarly, for bus routes, the missing bus distance can be computed by adding up the linear distance between each bus stop.

Car route

As in Table 4.4, the length of the car routes is the result of an algorithm with great circle distances and deviation factors [41]. The deviation factor and the average speed are the estimations of the distribution of the distance to street classes (Motorway, Rural, Urban). Motorways provide a more direct and faster route for driving compared to urban roads. As the proportion of motorways in the total length increases for longer distances, cars have a higher average speed in such cases. Additionally, the deviation factor decreases due to the more direct routes on motorways during long-distance drives.

Table 4.4: car speed and deviation factor

Linear distance	Deviation factor	car Average speed
<=100 km	1.35	60 km/h
100 km - <=500 km	1.25	90 km/h
500 km - <=1000 km	1.15	95 km/h
>1000 km	1.1	100 km/h

4.3. WTW emission estimation

aircraft Emission estimation

There are different aviation emission models have been developed, and each of these approaches makes some assumptions and presents different capabilities and limitations. FEAT [37] the advantage of leveraging fuel estimation accuracy and computational efficiency. And the final formula only requires distance and aircraft type as sole inputs.

The FEAT model contains two steps:

- a high-fidelity flight profile simulator generates a flight profile and calculates the fuel needed for the specific flight. It is based on various datasets, including BADA aircraft performance coefficients, ICAO Engine Emissions Databank.
- a reduced order fuel consumption approximation : Firstly, it uses the high-fidelity flight profile to generate emissions for different distance points. And then the ordinary least squares are conducted per aircraft. After model reduction, the fuel estimation only uses origin-destination airport distance and aircraft type as sole inputs.

The final formula is shown in 4.3. The specific aircraft type between the particular route is queried from Opensky and the great-circle distance is calculated as in Equation 4.1 as stated in Section 4.2.

$$F_i = \alpha_i \cdot d_{\mathsf{g}}^2 + \beta_i \cdot d_{\mathsf{g}} + \gamma_i \tag{4.3}$$

Where F_i is the fuel burn of a flight in kilograms. d_g is the great circle distance GCD between airport pairs given in Equation 4.3. The α_i, β_i, γ_i are aircraft-type specific parameters driven by using ordinary least squares regression

The FEAT model contains total 133 aircraft types representing the complete set of aircraft in the global flight movement schedule in 2018. For the aircraft type that does not exist in the FEAT model, a similar aircraft type from the FEAT model will be mapped to it.

The TTW emission of an aircraft is the direct emission from fuel combustion. The Equation 4.4 shows how to transform fuel burn to the CO_2, CH_4, and N_2O emission per passenger. For the CO_2 emission, The fuel burn first multiplies with the emission factor- 3.15 kg/kg. In order to account for the non-CO2 effects of aviation, a factor of 1.9, as recommended by the UK Government (2019), was applied to the CO2 emissions. For calculating the CH_4 and N_2O emissions, 0.0005 g/MJ and 0.002 g/MJ were assumed. The assumed heat value of the fuel is 43 MJ/kg of fuel based on Baumeister [26] n_s and l_f represent the payload and occupancy.

In the FEAT model, the payload is modeled using an average load factor of 81.9% for the passenger on board [42] during 2018. This paper keeps consistent with this parameter.

$$\begin{aligned} CO_2 &= \frac{(fb \times 3.169) \times 1.9}{(ns \times lf)} \\ CH_4 &= \frac{(0.0000005 \times fb \times hv)}{(ns \times lf)} \\ N_2O &= \frac{(0.000002 \times fb \times hv)}{(ns \times lf)} \end{aligned} \tag{4.4}$$

The $CO_{2,eq}$ emissions per passenger is a method to convert amounts of other GHG gases to the equivalent amount of CO_2. All transportation modes' $CO_{2,eq}$ were calculated based on IPCC's Fifth Assessment Report [43]:

$$CO_{2,eq} = CO_2 + CH_4 \times 28 + N_2O \times 265 \tag{4.5}$$

In addition to direct emission calculations, the final thesis paper will also analyze other emissions during the entire life cycle assessment (LCA), including manufacturing, maintenance, and fuel production.

Railway emission data

Rail can be classified into two types: electric rail and diesel rail. Diesel trains emit carbon dioxide through the combustion of diesel fuel, whereas electric trains run solely on internal electric motors, resulting in no direct carbon emissions. However, their emissions originate from the electricity generation process, which primarily involves the burning of fossil fuels or coal at the Well-to-Train (WTT) stage.

The occupancy rate of a transportation mode is a crucial factor in determining its energy efficiency per passenger. The difference between a mode of transport being almost empty or 80% occupied can significantly impact its environmental performance, making it either the best or the worst choice.

The European Environment Agency [14] assumes average occupancy rates of 66% for High-Speed Rail (HSR) and 36% for InterCity/Régional Express (IC/RE) trains, as illustrated in Table 4.5. For a 30-seater bus, the occupancy rate is around 66%, equating to roughly 20 passengers on board.

Table 4.5: rail type in Europe

Transport Service	Power type	Occupancy rate	capacity
High-speed	Electric	66%	500
Intercity	Electric, Diesel	36%	180
bus	diesle	66%	30

When an average occupancy rate of 66% is here considered and using the Dalla Chiara average figure [9], the final specific energy consumption of HST results in 0.057 kWh/pkm. This is consistent with previous studies.

The energy consumption per pkm is then multiplied by average electricity emission factors to get CO_2 in terms of kg/pkm. The choice of what average electricity emission factors to use in the analysis addresses the concept of marginal electricity. The marginal electricity is as followed in Figure 4.7.

If the average electricity production emission factors are used(275 $gCO_{2,eq}/kwh$), the WTW emission for HSR is around 15.7 $gCO_{2,eq}/pkm$

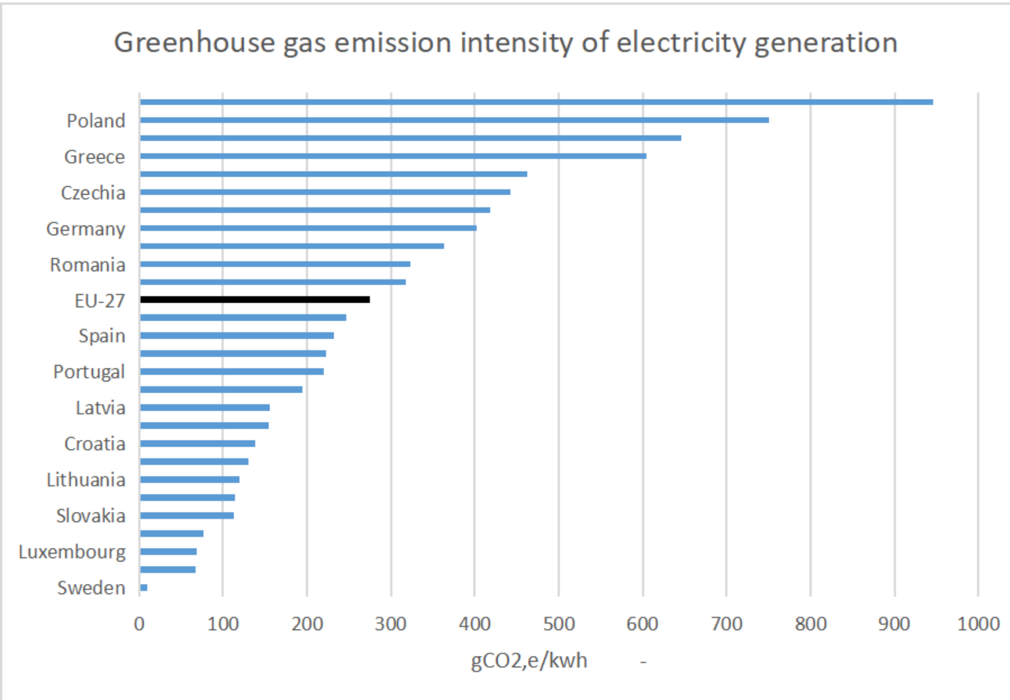


Figure 4.7: The GHG intensity per year by country

For the conventional intercity service inside the EU, Claus [44] suggests an average 40 $gCO_{2,eq}/pkm$ without distinguishing the electricity and diesel. Based on data from Schroten et al [45] and using the assumed occupancy rate, the energy consumption for electricity IC and diesel IC is calculated to be 0.083 KWH/pkm and 0.022 L/pkm, respectively.

Using the average EU-27 emission intensity, the electricity IC emission is 23 $gCO_{2,eq}/pkm$. After multiplying the diesel emission factors by the diesel train fuel consumption, the diesel train emission is approximately 60 $gCO_{2,eq}/pkm$. Table 4.6 gives a summary of the energy consumption by train.

Table 4.6: energy consumption of different types

Regional	category	energy consumption
EU-27	HSR	0.06 kwh/pkm
EU-27	electric Intercity	0.083 kwh/pkm
EU-27	diesle intercity	0.022 L/pkm

Bus and Car emission Calculation

This paper calculates the emission of buses and car by different propulsion systems. Three main categories(diesel, electric, petrol) are considered for the car.

Nowadays, The main bus fuel type is still diesel in EU-27, accounting for around 68.8% percent of new buses in 2021. while electric accounts for 10.6%. For the long-distance bus company like Flixbus, they are still mainly run on diesel, with the electricity bus only running on a few routes. For the scope of this paper, only a diesel propulsion bus is considered. Three main types are discussed here for the car: diesel cars, petrol cars, and electric cars. With the hybrid car gradually enlarging the market percentage(22.6% in 2021), the hybrid car emission will be discussed in the final thesis.

The $CO_{2,eq}/pkm$ result shown in Table 4.7 is based on the calculation from Claus Doll [44]. Occupancy rates for passenger transport are considered constant across distance bands and propulsion systems for each vehicle category: 1.6 passengers per passenger car, 20 passengers per bus or coach(obtained from [44], calculated by the passenger flow and the total vehicle on road number)

Table 4.7: Emission factors of different passenger transport modes in EU27

Transportation method	WTW Emission factor($gCO_{2,eq}/pkm$)
Ground bus diesel	80
Private car electric	69
Private car diesel	139
Private car petrol	149
HEV	85
BEV	52

4.4. LCA emission analysis

The LCA emission includes the entire cycle as indicated by Akerman [28]:

- Construction, maintenance, and operation of infrastructure
- Manufacturing and maintenance of vehicles
- Production and transport of fuels/electricity
- Vehicle use (i.e. direct emissions from vehicle operation

The TTW emission refers to the last one as the direct emissions from the operation. The WTT emission is the production and transport of fuels/electricity.

Michel Noussan [46] collected the LCA emission from previous studies per transport mode. For the car and bus, the LCA does not consider the impact of road construction and maintenance, since the road is shared across several different modes. The different car technologies' LCA emission shows a significant difference. The median values for traditional fossil-based technologies are generally higher than those of electrified options, The median value for gasoline cars is 235 g/pkm, while 138 g/pkm for the Battery electric vehicle. The average difference between WTW and LCA emissions is around 6 $gCO_{2,eq}/pkm$ considering all the types of cars.

The airport infrastructure and operations emissions are estimated by Messmer and Frischknecht as around 11.68 $gCO_{2,eq}/pkm$ [47], which does not take the aircraft maintenance and production emission into consideration. The Michel Noussan [46] concludes the mean emissions between the difference of WTW and LCA is around 34 $gCO_{2,eq}/pkm$.

The choice of considering the impact of the rail infrastructure remains debated, it is related to various factors, such as the transport amount served by the network. The results show a high variation. The International Union of Railways [48] proposes to consider an additional 5 $gCO_{2,eq}/pkm$ for rail in order to include emissions to include infrastructure, maintenance, and manufacturing carbon costs.

The HSR infrastructure emission has a different value from the conventional rail since the HSR has a more dedicated infrastructure. For the case in Spain, [49], the author estimates the average footprint is 18.24 $gCO_{2,eq}/pkm$ based on transport density and annual emission. The result shows a large difference per route, the HSR emission ranges from 12 $gCO_{2,eq}/pkm$ to 59 $gCO_{2,eq}/pkm$.

Overall, the environmental impact of public transport infrastructure construction and maintenance can vary significantly depending on the specific route. A case-by-case analysis is necessary to determine the actual impact of LCA on the environment.

4.5. Time consideration

When considering these modal shifts, not only emissions but time and passenger characteristics should be considered. Most travelers are only prepared to switch to more environmentally-friendly modes of transport if costs and time are comparable. The weighted perceived TT for each alternative i and passenger type j is thus obtained from the following formula[50]:

$$TT_{ij} = IVT_{ij} + \mu OVT_{ij} \quad (4.6)$$

where IVT, OVT, and μ are the in-vehicle time (time onboard), the out-of-vehicle time (sum of departure waiting time and transfer times), and the out-of-vehicle time multiplier, respectively. According to Wardman et al. [51], the out-of-vehicle time multiplier is estimated to be 1.76 as passengers find time spent outside of the vehicle to be more inconvenient and bothering. The out-of-vehicle time for air travel includes check-in, security check, and early arrival wait time, the total is estimated to be 90 minutes for air travel. If there is a baggage claim or there is a congested airport that needs longer check-in time, the procedure can be longer than 90 minutes. For rail and bus travel, the out-of-vehicle time is more stable being around 10 minutes early at the station.

5

Preliminary Results

This chapter presents the result of the multi-mode built in the previous Chapter 4. In the first section, the ten chosen routes are analyzed, including a discussion of their distance, connection type, and quality and travel time. The next section compares the emission of the multi-mode results.

5.1. Route and connection analysis

In the preliminary analysis, ten pairs of origin-destination are selected for analysis in the first stage. Among these pairs, five have distances lower than 500km, which is considered the most competitive distance for rail travel. Another four pairs have distances ranging from 500km to 800km, and one pair between Paris and Barcelona has a distance of 827km. The final pair among the ten selected pairs, from Schiphol airport to Madrid airport, has the longest distance of 1459km. Three pairs are domestic flights, while the remaining seven are cross-country intra-EU flights. A comparison of the distances is provided in Table 5.1. The bus distance is set equal to the car distance in the preliminary simulation. In the next step, the bus distance will be determined based on the GTFS.

Table 5.1: travel distance calculation in EU27

origin name	destination name	air travel distance	bus/car travel distance	train travel distance
Athens Intl Airport Elefterios Venizel	Thessalonik Makedonia	302	378	407
Brussels Airport	Frankfurt Am Main	304	380	411
Frankfurt Am Main	Hamburg	411	473	555
Schiphol	Paris Orly	435	500	588
Barajas	Barcelona - El Prat	483	555	652
Barajas	Lisboa	515	592	695
Milano Malpensa	Paris Orly	592	681	799
Milano Malpensa	Wien Schwechat	654	752	883
Barcelona - El Prat	Paris Orly	827	951	1116
Schiphol	Barajas	1459	1605	1970

In these 10 pairs, a total of 5 pairs are linked by the direct HSR line from the GTFS database. The link between Athens and Thessaloniki can be traveled by direct Intercity. The left four routes need a transfer. It is concluded in Table 5.2.

The pure flight time between the airport has an absolute advantage over the rail transfer. However, the check-in and security process at the airport needs abundant more time compared with rail travel. After adding the extra time, there are some advantages over some routes.

As in Table 5.3, there are three routes where rail travel time is less than the aircraft: Athens-Thessalonk, Schiphol-Paris Orly, and Madrid-Barcelona. Among the three pairs, only Athens-Thessalonik is offered by Intercity travel. It proves that on the short travel distance below 500km, Intercity can still play the role of an option or cooperate with HSR to substitute air. Among these three pairs, the maximum air distance is 515km. From Barcelona to Paris, where the distance is around 1116km by rail, although there is a direct HSR, the HSR exceeds 2.5 hours then the air travel. For the remaining routes without HSR connectivity or those only partially served by HSR, their travel time is not competitive with air travel. As shown in Figure 5.1, when the distance is below 500km, air travel provides a similar travel time to other ground transportation options. When the distance is larger than 500km, the air shows an uncompetitive advantage in travel time. Additionally, for poorly connected rail pairs, for example from Madrid to Lisbon, the travel time by rail can exceed that of buses and cars.

Table 5.2: airport pairs connection

origin name	destination name	rail travel time(minutes)	travel type
Athens Intl Airport Elefterios Venizel	Thessalonik Makedonia	164	direct IC
Brussels Airport	Frankfurt Am Main	209	direct HSR
Frankfurt Am Main	Hamburg	289	direct HSR
Schiphol	Paris Orly	180	direct HSR
Barajas	Barcelona - El Prat	149	direct HSR
Barajas	Lisboa	610	conventional
Milano Malpensa	Paris Orly	409	part of HSR
Milano Malpensa	Wien Schwechat	690	part of HSR
Barcelona - El Prat	Paris Orly	391	direct HSR
Schiphol	Barajas	1260	part of HSR

Table 5.3: airport pairs travel time

origin name	destination name	air travel time	air travel with extratime	rail time
LGAV	LGTS	33	191	164
EBBR	EDDF	41	199	209
EDDF	EDDH	47	205	289
EHAM	LFPO	54	212	180
LEMD	LEBL	53	211	149
LEMD	LPPT	56	214	610
LIMC	LFPO	64	222	409
LIMC	LOWW	62	220	690
LEBL	LFPO	82	240	391
EHAM	LEMD	130	288	1260

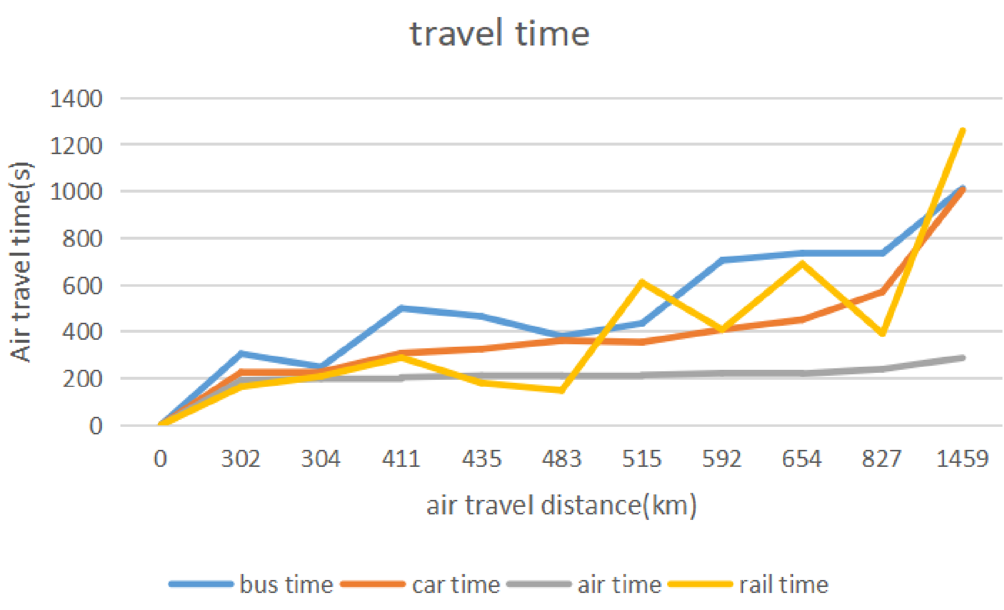


Figure 5.1: Time travel for 10 pairs

5.2. Direct emission comparison

Figure 5.2 shows that different aircraft types have a significant impact on emission performance, even when operating on the same route. For instance, on the Schiphol airport to Madrid route, the Boeing 737 generates the highest emissions, with 39 kg more GHG emissions per passenger compared to the Boeing 787-8. This difference is attributable to the fact that the Boeing 787-8 is a wide-body aircraft with a higher capacity than the Boeing 737, resulting in lower per-passenger emissions. It can be driven that the choice of aircraft type also largely influences the emission result.

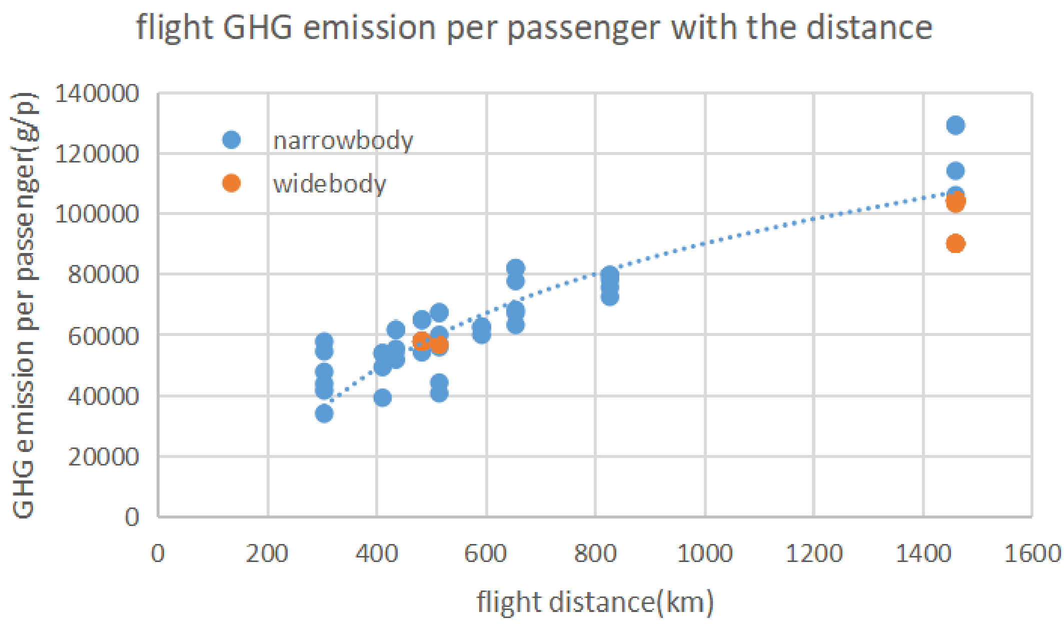


Figure 5.2: Emission per kilometer for aircraft

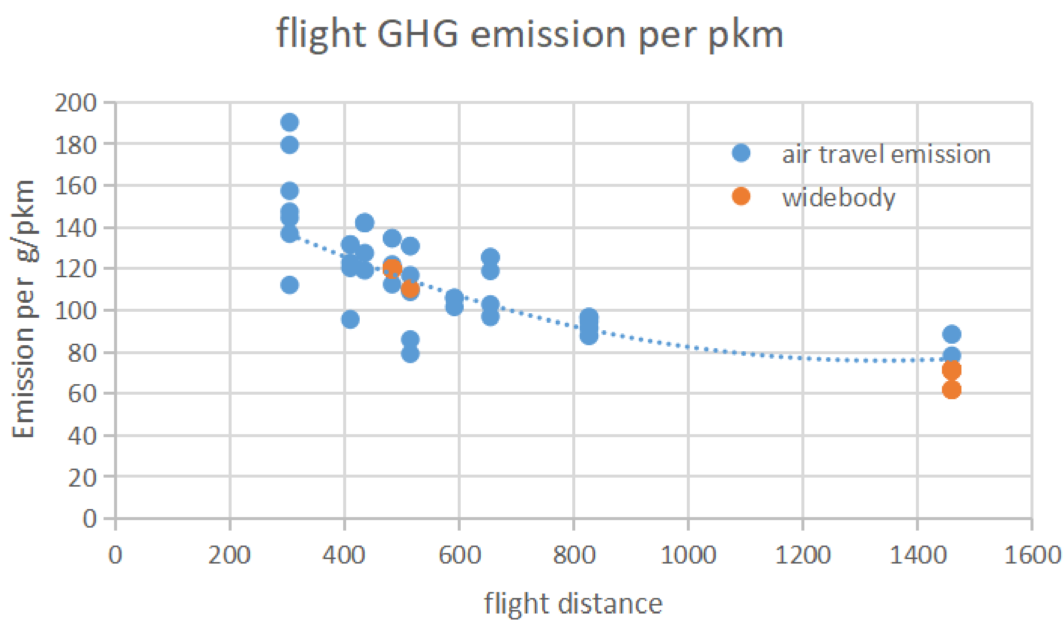


Figure 5.3: Emission per pkm for aircraft

From Figure 5.3, it can be seen that among the flights, short-haul flights produce the highest amount of GHG emissions per passenger kilometer, even though longer flights mean more emissions in absolute terms. The GHG per passenger kilometer decreases with the travel distance increasing, for the reason the highest emission stage is the take-off and landing, which occupies less in the long-distance flight.

The emission result is summarized in Figure 5.4. When comparing with ground transport, the results here presented confirm a remarkable advantage of rail compared to other transportation methods, with regard to direct $CO_{2,eq}$ emissions per passenger.

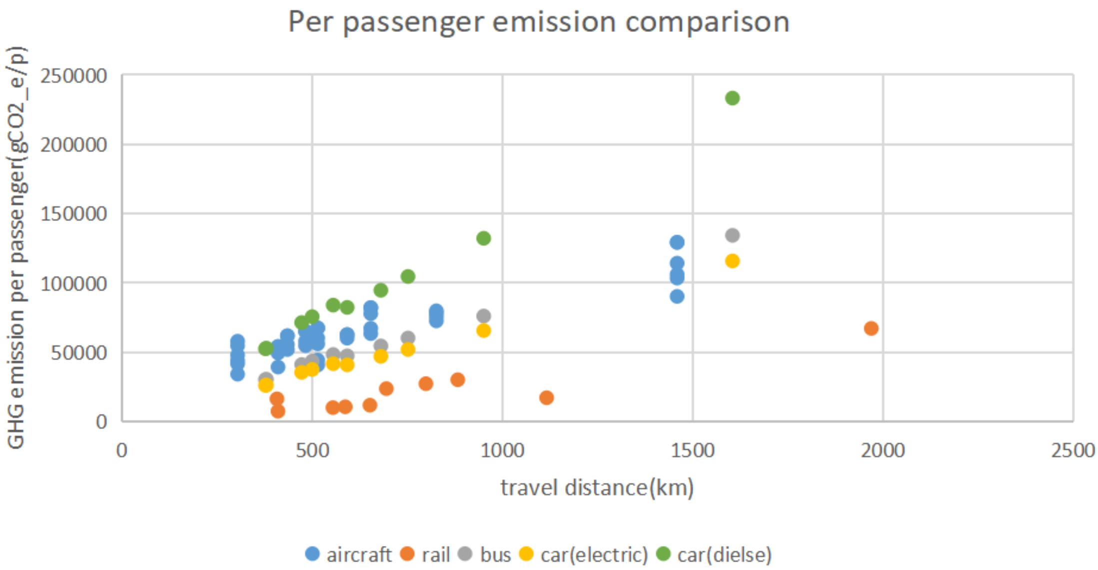


Figure 5.4: Emission per passenger kilometer for aircraft

Considering the travel between Frankfurt and Brussels Airport, the emission traveling by air is more than seven times higher than traveling by HSR as in Figure 5.5.

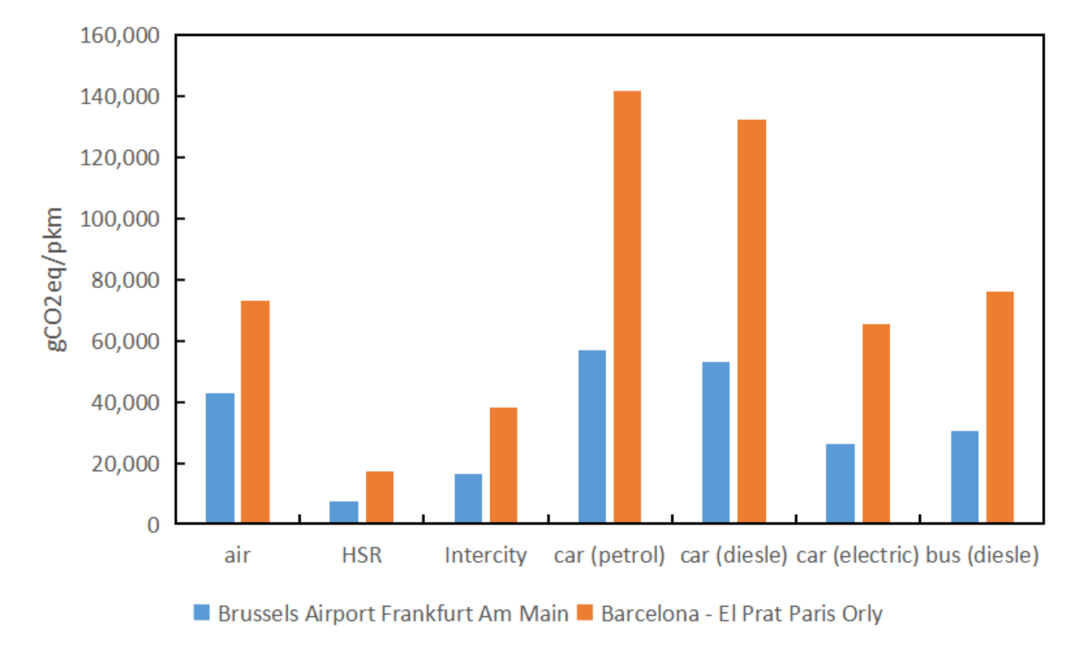


Figure 5.5: GHG emission pkm comparison for two pairs

The second sustainable choice of travel is the electric car or diesel bus. However, for the diesel car, the emission results show it is one of the worst transport modes, together with the airplane. The emission of an average of 1.6 people traveling in a diesel or petrol car is the highest of all travel options on relatively longer distance routes. As in Figure 5.5, from Barcelona to Paris Orly airport has a distance of around 827 km, its car emission is much higher than air. if traveling in a fully occupied car, with four people, the car result will have a lower emission. The occupancy influence will be discussed in the final report.

6 Planning

This chapter outlines the methods for addressing the issues and challenges identified in the preceding sections

6.1. Model extension and calculation

At the next stage, the model will run on all 526 pairs of origin/destination. The basic model used in the calculation in Chapter 5 only considers the direct route between the origin and destination. The model will be extended to include all routes that require no more than two transfers, based on the methodology described below.

The long-distance HSR overnight train largely enlarges the range of the replacement range to 2000km as stated in Chapter 2. The data from the main operator of the long-distance HSR will be looked up and added to the database. Upon the first check, the main sleeper train companies include OBB, and Trenhotel. OBB night jet GTFS is currently available to download, and its route maps are shown in Figure 6.1. However, information about Amsterdam is missing in the OBB GTFS. In the next step, the missing information about the trips will be examined on the OBB website [52] and manually add to the GTFS timetable.

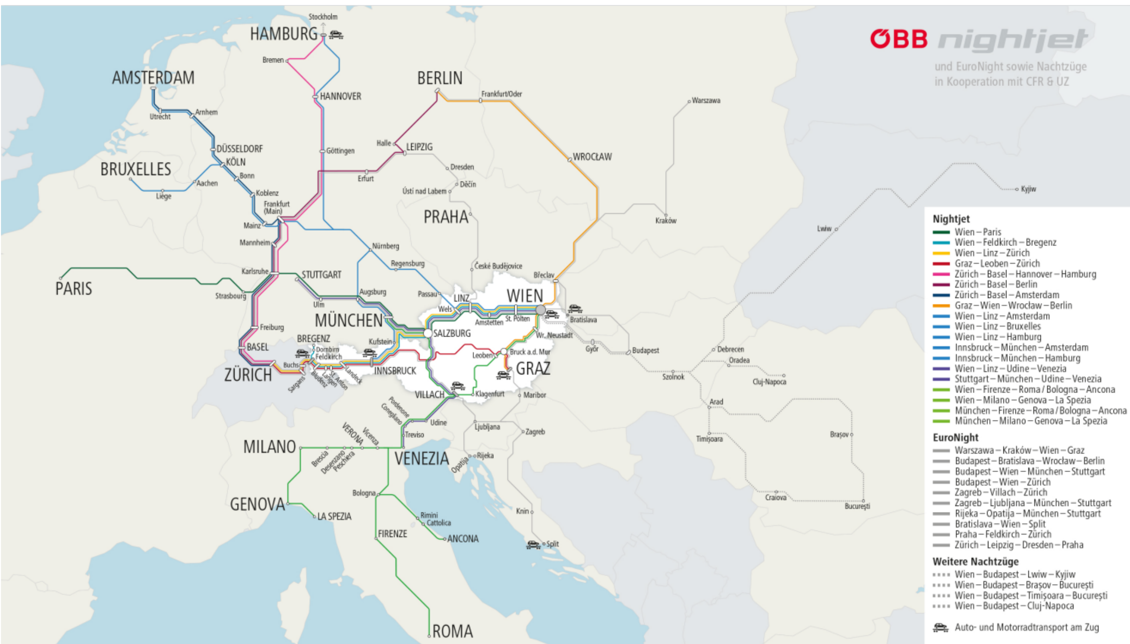


Figure 6.1: The OBB nightjet map(Source:OBB nightjet website[52])

The previous research takes public ground transport(bus, rail) as the sole solution to substitute air travel. Combining these two modes can have a higher transport frequency and give travelers more flexible options regarding time. This paper will integrate their GTFS to consider emissions and other related effects.

6.1.1. Multi-stop ground transportation

The direct calculation only considers the direct route between the origin and destination. The next step will program to calculate the routes with no more than two transfers. The steps of finding trips with no more than transfer are shown in Figure 6.2. On the transfer stops, which are called $stop_{id,reorig}$ and $stop_{id,redes}$ in Figure 6.2, the transfer time is limited between 10 minutes and 60 minutes. And if the middle route has the same $trip_{id}$ as the first route or the last route, it means there is no transfer happening, which indicates a direct route. The transfer time is not be applied to these routes. When merging the GTFS from the different operators and in different countries, the $stop_{id}$ is not consistent. In the process of finding transfer stops $stop_{id}$, shown as the $stop_{id,reorig}$ and $stop_{id,redes}$ in Figure 6.2. The stops have a distance within 800m distance of the $stop_{id,reorig}$ and $stop_{id,redes}$ and are queried by the stop's coordinates. These stops are also be included in the gathering of the origin/destination-related stops.

Furthermore, in the final thesis, GTFS of bus, and rail will be merged to find the route where the bus cooperates with rail. The route planning procedure is the same as the Figure 6.2.

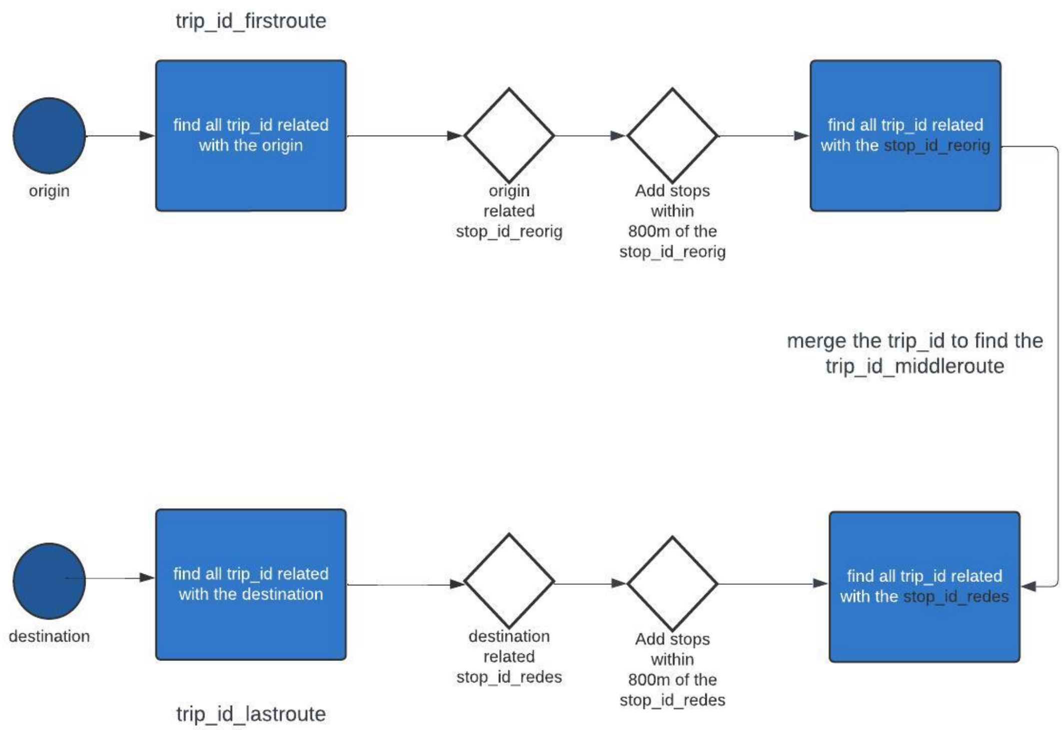


Figure 6.2: The process of finding no more than two transfers route in GTFS

6.1.2. Time and cost, frequency integration, reliability analysis

The simulation results presented in Chapter 4 only discuss the traveled time and emission. In the next step, this paper will analyze three other effects that are crucial to the traveler's choice of transport systems: travel time reliability, travel cost, and frequency of service.

For the travel cost, it is difficult to collect the rail, and bus price information on a large scale. This paper will select the pairs from different distance ranges to compare their cost information. The cost of public transfer will be queried from the Rome2Rio website. The travel time reliability by bus, rail operators, and airline operators will be studied in the final paper. The plan is to look up the average punctuality of different operators and areas.

Regarding the travel frequency, car transport is very flexible in this aspect. However, in the case of rail and air transport, travel is according to set train schedules and flight plans. A schedule with higher frequency services is more attractive to travelers, with higher flexibility in choosing the time. And frequency determines how many passengers can be transported in one day, which also influences the emission from the transport. The frequency of the rail and bus will be counted based on GTFS. For air travel, the frequency will be counted by the flight number within one day.

6.2. Sensitivity analysis

For all the assumptions and uncertainties, the sensitivity analysis will be conducted to evaluate the result. The assumptions value is included as followed:

- The occupancy level is the single most important factor across all the modes considered. A change in the occupancy level can make a transport method the most sustainable or least method. The aircraft occupancy is all set to be 80% in the preliminary simulation, however, there is an obvious difference exists between the wide-body and narrow-body aircraft. Additionally, the occupancy varied greatly depending on the route. This sensitivity will be further calculated and analyzed in the final report.
- Car speed assumption, the car speed is subject hugely to the traffic on the road. The result of the uncertainties of the speed of the car will be discussed in the next step.
- LCA emission. The emission of public transport infrastructure construction and maintenance can vary significantly depending on the specific route. This study will examine the effect of the variations in LCA emission.

6.3. Verification and validation

After the model extension, the model will run all the cases. The result will be checked whether it behaves as we anticipated and whether the results can be visualized. Regarding the validation, the result will be compared with the EEA report result [14], which contains aircraft and rail emission and travel time calculations for the 20 pairs of routes within Europe.

7 Conclusion

Over the last few years, the exponential growth of air traffic has led to aviation being the fastest-growing source of emissions that contribute to climate change, raising the issue of sustainable growth in air transport to the public. One of the solutions designed to reverse this trend is to enable the modal shift to alternate aircraft toward greener transport modes where technically possible. The other one is to integrate multiple transport methods to partially substitute air travel.

In the literature review sector of this report, previous research regarded the competition and cooperation between the transport sector is summarized. In the competition area, researchers mainly studied the modal shift from aircraft to land-based transportation modes, in particular replacing aviation with HSR. HSR can compete with aviation on distances up to 800 km and that competition can take place on some routes even up to 1000 km. One study also shows that NHSR in Finland remains competitive against air travel on distances up to 400 km in terms of travel time. and would result in a 95% emissions reduction. On the model cooperation, Other studies also show that HSR-Air cooperation instead of substitution can also be beneficial to the GHG emission and can also increase the airport hub capacity.

This paper studies the environmental effects of the modal shift from short-to-medium range air to ground transport in EU-27 and also considers travel cost, frequency, time, and punctuality. This research fills an existing research gap there are few studies on how NHSR plays a role in substituting air travel in EU, whether solely or cooperating with HSR. The long-distance bus, overnight train, and car is also examined. Another gap that this paper fills is that currently most of the research's railway data is input manually by searching online, bringing difficulty to reproduce the result and prevent the analysis on a large database. This paper will introduce the model of using GTFS to find routes of rail and bus. The build of the model facilitates the extensive analysis of the rail data on a large scale and is not restricted to the region.

In the preliminary result, 10 pairs of origin/destination are studied to compare the emission and travel time. It shows the consistency with some previous papers that HSR can largely reduce the per passenger emission on the route shorter than 500km and without deteriorating much travel time. HSR largely increases the possibility of replacing the air travel. However, it is hard to give a certain distance band for the rail substitution range, since the quality of the rail and the portion of HSR on the route differ largely. When the distance is up to 1000km, the aircraft still dominates the market by providing not replaceable time of travel. And compared with short-distance air travel below 1000km, the aircraft emits less CO_2 per passenger when the distance is longer. Air travel emission also relies heavily on the aircraft type. For the widebody aircraft,its emission per passenger is lower when considering its occupancy is the same as the narrowbody. Capturing the customers from car travel to train or bus also can largely improve the environment. Diesel and petrol cars can be more unsustainable compared with aircraft when the distance is larger than 800km.

In the final paper, the result of the WTW and LCA emissions comparison between air travel and ground transportation among the total selected 526 routes will be calculated. A sensitivity analysis will be made to verify and validate the model. And the unsolved questions mentioned in the Planning will be answered in the final paper. The final result attempts to give individual travel an optimal option of travel on a specific route, integrating the environmental and travel factors. This paper will also make recommendations for future transport network construction and policy.

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