MSc Thesis

Streamlining Multi-Stop Flights With Ground Transportation

AE5310: Thesis Control and Operations

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Streamlining Multi-Stop Flights With Ground Transportation

by

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Preface

Presented before you is my master's thesis, marking the culmination of my academic journey of six and a half enriching years at TU Delft. The focus of my research is on intermodality and its application to multi-stop flights. The aim is to reduce aviation emissions while ensuring that the travel time for passengers remains comparable. I sincerely hope that this work reaches policymakers and inspires the aviation and rail industries to collaborate across borders, providing seamless low-emission mobility solutions across Europe.

I would like to express my deepest appreciation to Dr. Junzi Sun, my supervisor, for his invaluable guidance and expertise. His support made working on my thesis an enjoyable and rewarding experience. Additionally, I am grateful to Prof. dr. ir. Jacco Hoekstra for his constructive feedback and critical input, which significantly enhanced the quality of my work.

I extend my heartfelt gratitude to my family for their unwavering support, valuable suggestions, and insightful ideas. I am also deeply grateful to my girlfriend for her constant presence and encouragement. Finally, I would like to express my appreciation to my friends for their trust in me. Thank you all for being an integral part of my life.

K.A. Bislip
Delft, February 2023

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
ADS-B	Automatic Dependent Surveillance-Broadcast
API	Application Programming Interface
ATM	Air Traffic Management
CO2	Carbon Dioxide
CO2-eq	Carbon Dioxide Equivalent
D2D	Door-to-Door
ETL	Extract, Transform and Load
FSR	Full Service High-Speed Rail
G2G	Gate-to-Gate
GHG	Greenhouse Gasses
HSR	High Speed Rail
IATA	The International Air Transport Association
ICAO	International Civil Aviation Organization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCR	Low-Cost High-Speed Rail
MCT	Minimum Connecting Time
MSF	Multi-Stop Flight
NHSR	Non-High-Speed Rail
SAF	Sustainable Aviation Fuel
TTW	Tank-to-wheel
WTT	Well-to-tank
WTW	Well-to-wheel

Symbols

Symbol	Definition	Unit
d_a	Actual flown distance	[km]
d_g	Great circle distance	[km]
d_{g_d}	Direct great circle distance	[km]
d_{g_t}	Total great circle distance	[km]
F_i	Fuel burn	[kg]
km	Kilometer	[km]
kg	Kilogram	[kg]
LCA_f	Flight life-cycle assessment emissions	$[kgCO_2e]$
t^{GT}	Ground transit travel time	[minutes]
t^{IMCT}	Intermodal connecting time	[minutes]
t^{FFT1}	Filed flight time flight leg 1	[minutes]
t^{FFT2}	Filed flight time flight leg 2	[minutes]
t^{D2K}	Door-to-kerb time	[minutes]
t^{K2G}	Kerb-to-gate time	[minutes]
t^{G2K}	Gate-to-kerb time	[minutes]
t^{K2D}	Kerb-to-door time	[minutes]
WTW_f	Flight well-to-wheel emissions	$[kgCO_2e]$
λ	Longitude	[deg]
ϕ	Latitude	[deg]

List of Figures

List of Tables

Part I

Scientific Paper

Streamlining Multi-Stop Flights With Ground Transportation

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***Abstract*—Passenger transportation in Europe is often duplicated using modes of transportation which are environmentally inefficient. Quantifying the carbon dioxide emission inefficiencies of flights versus transit is beneficial to understand the potential savings of a modal shift. In this paper, we analyze the emissions in Europe from multi-stop flights using flight data from March 2019. The excess emissions are quantified by comparing each multi-stop flight with an intermodal journey that does not exceed 60 minutes of extra travel time. We find that on average, transfer passengers using intermodality can reduce their journey's total (segment) well-to-wheel and life-cycle assessment emissions by 33% (80%) and 30% (72%), respectively. 840 thousand (19 % of total) transfer passengers starting or ending their journey in Europe can skip the feeder flight while saving an average of 28 minutes of door-to-door travel time. For air travellers taking intra-European multi-stop flights, 157 thousand transfer passengers (10% of the total) do not have to even enter an airport. Further insights regarding the European mobility vision are made, with recommendations for various stakeholders.**

***Index Terms*—intermodal transportation, door-to-door, multi-stop flights, European mobility, emissions, modal shift**

I. Introduction

Air traffic growth has led to increasing concerns about the impact of aviation on the climate. In response to these concerns, efforts have been directed towards developing technological and procedural solutions that can reduce the carbon footprint of the aviation industry. Despite these efforts, flight and air traffic management inefficiencies, as well as congestion-related delays, remain a significant challenge that needs to be addressed.

The hub-and-spoke network structure offers more flight options for travellers and provides more efficient service for routes with low demand. Airlines benefit from higher operational density and can offer more frequent flights [1]. However, travellers face longer travel times because of the layover at the hub airport. By using feeder flights, the congestion issues at hub airports are amplified as airlines schedule flights in banks with arrivals and departures happening at around the same time. For some multi-stop flights (MSFs), this network structure also leads to duplication of air and rail capacity in Europe in order to feed passengers into hub airports.

Sustainability and mobility are high priorities for Europe. The European Green Deal calls for a 90% reduction in greenhouse gas emissions from transport by 2050 compared with 1990 [2]. The European Commission saw that the airport capacity "needs to be optimized and, where necessary, increased to face a growing demand for travel ... which could result in a more than doubling of EU air transport activities by 2050. In other cases, (high speed) rail should absorb much medium distance traffic" [3]. Europe's mobility goal, the Flightpath 2050 aims to enable 90% of citizens to reach any place in Europe within 4 hours door to door by 2050, for journeys including an air segment [4]. In order to address these objectives, an out-of-the-box solution is needed to facilitate a shift towards the most sustainable but also time-efficient transport modes. This paper proposes to explore the possibility of integrating ground transportation and air travel in Europe. By doing so, it may be possible to reduce carbon dioxide emissions while maintaining a similar door-to-door travel time for passengers.

The current paper has a threefold contribution. The first is a novel method developed to recreate realistic 1-stop MSFs and estimate their associated number of transfer passengers. Secondly, this paper integrates flight data with ground transportation data to create potential intermodal passenger journeys. Thirdly, this paper shows that integrating MSFs with existing ground transportation can reduce travel time and environmental footprint for passengers, both in terms of well-to-wheel (WTW) emissions and life-cycle assessment (LCA) emissions. The WTW emissions of aircraft and the various ground transit options cover both the well-to-tank (WTT) as well as the tank-to-wheel (TTW) emissions. The TTW emissions result from direct combustion exhaust emissions, while the WTT emissions occur during the production and distribution of electricity and jet fuel. The LCA emissions include the WTW emissions and also emissions from maintenance, manufacturing of the vehicle/aircraft, and construction of infrastructure to support the operations.

The remainder of the paper is structured as follows. Section II describes the method for reconstructing MSFs and estimating transfer passengers. In Section III, the method for retrieving and integrating ground transportation data to create intermodal journeys is proposed. In Section IV, the estimation methods of carbon dioxide emissions for both flights and ground transportation is shown. Then, in Section V, some applications of the model are made and a sensitivity analysis of the model is performed. Penultimately, Section VI discusses the limitations of the model described in this paper and insights into the future of European mobility are made with recommendations for the different stakeholders. Finally, conclusions are drawn in Section VII and some recommendations for future work are given.

II. Modeling Multi-Stop Flights

This section introduces the method for reconstructing realistic multi-stop flights (MSFs) from individual flights. Also, the associated transfer passengers are quantified on each MSF.

A. Reconstruction of Realistic Multi-stop Flights

Flight plan data is necessary to understand where a flight starts and ends, when a flight took place, which airline flew what kind of aircraft and whether it was a commercial passenger flight. EUROCONTROL's R&D data [5], hereafter named flight data contains four months of each year of detailed individual flight plan data. The month of March 2019 is used for analysis purposes. The geographical scope of the flight data includes all flights originating from, arriving at, or flying over one of the countries within the operational area of the EUROCONTROL Network Manager. E.g., international flights starting from the United States and ending at a European airport would be present in the data. The flight data contains actual and filed flight plan data starting from departure from the gate, i.e., the off-block time, until arrival at the destination airport at the time of landing. To estimate the time of arrival at the gate, i.e. on-block time, taxi-in times are also made available by EUROCONTROL [6]. In this paper, it is necessary to find 1-stop MSFs with at least one flight leg replaceable for intermodality. Hence, 1-stop MSFs must have airport combinations with at least two airports in the area of interest within Europe connected by land with each other and that have sufficient Google Maps data within Europe. 310 airports are within the area of interest, as can be seen in Figure 1.

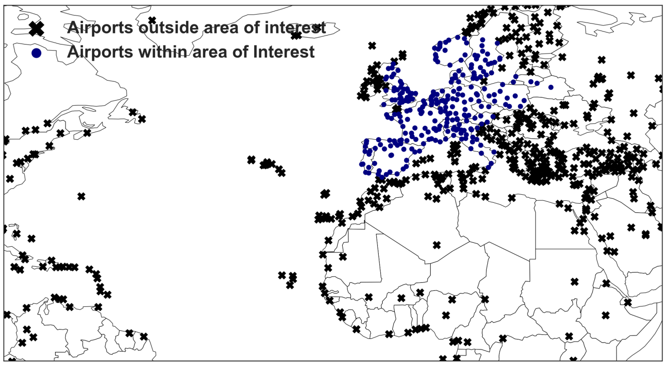


Fig. 1: Airports considered for intermodality within flight data. Map is clipped for clarity.

The flight data was enhanced by merging it with alliance data from the three major airline alliances: Star alliance, Skyteam, and Oneworld. This was done to enable inter-airline transfers within the same alliance and to create more realistic MSFs. These inter-airline transfers, also called codesharing agreements, are a key feature in airline alliances to connect an airline with a non-serviced market. Together these alliance flights form over 72% of the cleaned flights' dataset.

The flight data were cleaned to recreate commercial MSFs. For this, only traditionally scheduled flights which are representative of normal operations were kept. Low-cost airlines were filtered out as they do not typically book MSFs. Flights with unknown operator International Civil Aviation Organization (ICAO) codes given by 'ZZZ', unknown aircraft types given by 'ZZZZ', and unknown airports given by 'ZZZZ' were removed [7]. Flights with the same origin and destination airport were removed. From the original 789 thousand flights, 453 thousand flights remain after cleaning.

Time and distance-based filters were created to exclude flights that were excessively outside of normal operations. For example, flights with more than 120 minutes of difference between actual off-block time and filed off-block time were removed. Flights shorter than 30 minutes, or longer than 19 hours were removed. Also, the difference between the filed and actual flight time in minutes must be smaller than 25%, to avoid flights with much delay. The coordinates of airports were used to calculate Haversine (or great circle) distance (GCD) between origin and destination airports given by the following equation:

$$d_g = 2r \arcsin \sqrt{\sin^2\left(\frac{\varphi_2-\varphi_1}{2}\right) + \cos\varphi_1 \cdot \cos\varphi_2 \cdot \sin^2\left(\frac{\lambda_2-\lambda_1}{2}\right)} \quad (1)$$

where

- φ_1, φ_2 are the latitude of point 1 and 2,
- λ_1, λ_2 are the longitude of point 1 and 2,
- r is the radius of the sphere, which for earth is 6372.8 km.

The flight would be excluded if the flight's actual flown distance (d_a) is 30% longer than the GCD (d_g):

$$0.98 \leq \frac{d_a}{d_g} \leq 1.30 \quad (2)$$

After filtering the data, 418 thousand flights remain. These remaining flights are used to create realistic commercial passenger MSF combinations, i.e., flights that air travellers would take in sequence. The individual flights were placed in departure and arrival timeslots of one hour by flooring the off-block times and on-block times, respectively. The flights were then merged on the same connecting airport using a 6-hour ahead moving time window. MSFs with the same origin and destination airport and MSFs with different airlines not within the same alliance are removed.

At this point, 5 million potential MSFs are found. However, not all of these are realistic. To make them realistic, six conditions are applied. Due to the uncertainty in the input parameters for these conditions, a sensitivity analysis is conducted which is given in Section V-C.

Consider the example of a passenger who boards a MSF starting from Amsterdam, makes a transfer in Beijing, and finally arrives in Brussels. Using this example two conditions are identified. Firstly, MSFs should have at least some minimum distance from the origin to the destination. For the baseline model, this parameter is set to 300 km. This was chosen using insights from existing routes. Secondly, the total Haversine distance travelled (d_{g_t}) should scale with the direct Haversine distance (d_{g_d}), it does not make sense to travel the world and back. To find the right sense scale (S), real intra-European and extra-European MSF routes are discovered using popular flight booking websites. A linearly decreasing scale with a minimum threshold was found to fit well with existing MSFs, as shown in Eq. 4, with the appropriate parameters. If

Condition	Parameter value
Minimum worth distance	300 km
Sense distance switch	2000 km
Sense ratio short-haul/long-haul	2.5/1.25
Minimum transfer time	70 minutes
Maximum transfer time	5 hours
Minimum frequency in both legs	1 flight per 2 days
Maximum direct flights frequency	1 flight per day

TABLE I: Baseline model condition initial parameters.

the sense scale S is larger than the total distance travelled d_{g_t} divided by the direct distance d_{g_d}, the MSF is kept.

$$S = -6.25e^{-4} \cdot d_{g\_d} + 2.5 \qquad for \quad d_{g\_d} < 2000km \quad (3)$$
$$= 1.25 \qquad for \quad d_{g\_d} \geq 2000km \quad (4)$$

A third condition is made to recreate the fact that airlines do not book MSFs if the passenger cannot make the connecting flight, usually with the help of the minimum connecting time which is given per airport. This data was not freely available, hence the minimum connecting time (MCT) was set as a constant of 45 minutes across all airports. The transfer time is defined as the difference between the on-block time of the first flight leg, i.e., when the first aircraft is parked, and the off-block time of the second flight leg. This transfer time must be larger than the MCT plus a 15-minute departure time buffer (assuming boarding closes about 15 minutes before the departure time) plus 10 minutes of deboarding time. The variation in deboarding time was not considered in this paper. The fourth condition looks at the maximum transfer time, as passengers tend to avoid MSFs with a large transfer time. Hence, if the transfer time to the second flight leg is larger than 5 hours, the MSF is filtered out.

The fifth condition considers a MSF irrealistic if there is not sufficient frequency in both flight legs by the same airline or alliance. For the baseline model, there must be at least 15 flights in both flight legs, which translates to about one flight every two days.

Finally, if there are more than a certain number of direct flights which go directly from the departure airport to the destination airport, a MSF would be considered irrealistic. These direct flights are only by a single airline or alliance, not the total direct flights combined by all airlines. The idea behind this condition is that passengers are assumed to select direct flights over MSFs. For the baseline model, a maximum frequency of 1 direct flight per day by any airline or alliance is allowed for a multi-stop route to exist.

After applying the aforementioned conditions, which are summarized in Table I, 1.9 million realistic MSFs for the baseline model remain.

B. Challenge of Estimation of Transfer Passengers

Estimating the number of transfer passengers on a given MSF is useful to understand the impact of shifting MSF passengers, or transfer passengers to intermodality. For future research on, e.g., passenger flows, knowledge of transfer passengers can be useful. However, the estimation depends on many unknown and sometimes interdependent factors. E.g., the airline, the load factor of the flight (which itself depends on many other factors such as the aircraft type), day of the week, season, origin and destination pairs or even the time of day to name a few. The number of transfer passengers on a certain flight is known by airlines but is not publicly available.

To estimate the number of transfer passengers it is first necessary to estimate the number of passengers on a particular flight. Using the aircraft type from the flight data, the flight data were merged with data on aircraft maximum seat capacities. To conform with the chosen carbon dioxide emissions model chosen, the worldwide average load factor of 81.9% provided by The International Air Transport Association (IATA) in 2018 is used [8]. In reality, the load factor of a flight depends on many different factors which are explained in Section VI-B. The maximum (single-class, high-density) number of seats available on an aircraft is provided by the aircraft manufacturer or was found in the EUROCONTROL Aircraft Performance Database [9, 10]. The limitation of using a single-class, high-density configuration is described in Section VI-B.

Now that the number of passengers on each flight is known, the connecting airport's transfer rate comes in useful for estimating the average number of transfer passengers. The airport transfer rate is a statistic of an airport determining the ratio of transfer passengers versus origin and destination passengers. The airport transfer rate is simply multiplied by the number of passengers on the first flight leg to find the number of transfer passengers. It is assumed that while there are variations between flights, over a month these differences average out. Several major hub airports publish their transfer rates. However, not all airports do, especially smaller airports. This data is available for purchase by SABRE market intelligence, which has been processed in a study on global transfer passenger developments by DLR & Sabre [11]. The data used by this study was kindly provided solely for this paper. Future work could perform desk research on major hub airports and assume a zero transfer rate for others.

Now the distribution of these transfer passengers transferring into other final destinations through the connecting airport must be reasoned. This is because there are usually more than one possible transfer flight a passenger can take. Therefore, a transfer probability is calculated using a normal distribution based on the transfer time for each possible transfer flight. For the baseline model, a mean of 2 hours of transfer time and 30 minutes of variance is used. This leads to at times an over-allocation of transfer passengers from many first legs into a second flight leg. In order to counteract this, the capacity of the second flight is divided by the total allocated transfer passengers and this ratio is limited to 1. This ratio is then multiplied by the previously calculated number of transfer passengers from a single flight leg 1 to normalize it.

III. Intermodal Alternative

In the previous section, the realistic multi-stop flights (MSF)s were reconstructed from individual flight data. In this section, these MSFs are converted to intermodal journeys, by replacing one or both flight legs. The basis for transit data

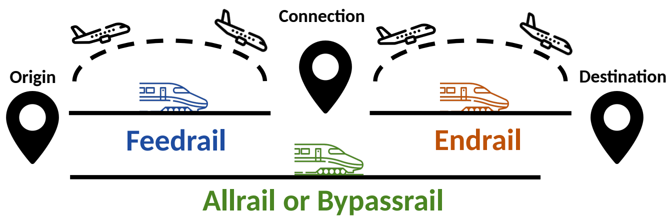


Fig. 2: The intermodal integration categories between the origin, connection, and destination airports: feedrail, endrail, allrail and bypassrail.

Journey Segment Time	Time
Door-to-kerb time t^{D2K}	33 minutes
Kerb-to-gate time t^{K2G}	114 minutes
Gate-to-kerb time t^{G2K}	31 minutes
Kerb-to-door time t^{K2D}	28 minutes

TABLE II: DATASET2050 airport access and egress average travel times [12].

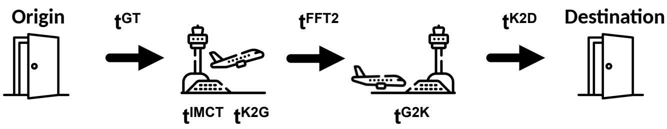
used is the Google Maps application programming interface (API).

A. Integration of Transit Data

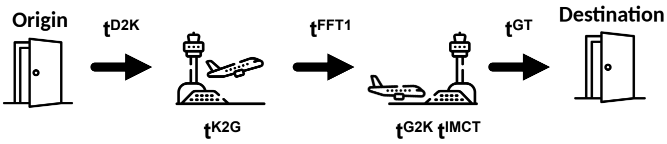
The Google Maps API can be used to find detailed transit journey data, including data per step of a transit journey. To query the API, the departure and destination locations are needed as well as the departure and arrival times. Furthermore, the preference for transit and trains were chosen for this paper. In this paper, it is assumed a journey starts and ends in an airport, this is further discussed in Section VI-C.

Four different categories were established for the MSFs in order to identify which segments could be replaced. These categories are visually displayed in Figure 2. Feedrail occurs if the first flight leg can be replaced by a 'feeder train'. Similarly, endrail is if the second leg can be replaced. Allrail and bypassrail occur if both legs can be replaced. The difference between allrail and bypassrail is that allrail must have all 3 airports in the area of interest. In contrast, bypassrail means only the connecting airport is not in the area of interest.

The arrival and departure times for transit were determined using the average airport access and egress times from Innaxis [12], given in Table II. Using the origin and destination airport and appropriate time to, e.g., arrive on-time for a flight, allowed querying the Google Maps API. The response data from the Google Maps API was extracted to derive some journey metrics such as travel distance and travel time, vehicle types, number of transfers, distance per step per country, transfer times, and so forth. The response contains four different alternative journeys. Only the fastest of these alternatives was kept. Also, to reduce the number of queries to the Google Maps API, timeslots of 1 hour were created for each route pair and only route pairs with more than 30 MSFs in a single timeslot were kept. The limitation of using the fastest alternative and the reduction of queries are discussed in Section VI-A.



(a) Feedrail Journey Travel Times.



(b) Endrail Journey Travel Times.

Fig. 3: The door-to-door intermodal journeys with corresponding travel times for feedrail and endrail. Allrail is not depicted as it is simply door-to-door.

The MSFs were integrated with ground transit to create intermodal journeys. This was done by taking into account the category of MSFs and the average airport access and egress times. For feedrail, ground transit must arrive on time to go from the connecting airport's kerb (entrance) to the gate of the second flight. For endrail, the transfer passenger switches to transit after leaving the first flight and going from the gate to the kerb of the connecting airport. Allrail flights do not have a timing constraint.

These intermodal journeys with the associated travel times for each segment are given in Figure 3. For feedrail and endrail the journey consists of airport access and egress times given in Table II, air-ground transfer times, ground transit travel time and in-flight times. For feedrail, the ground transit travel time t^{GT} is the time from the departure of the origin airport to the arrival at the airport. For endrail, t^{GT} is the time from the departure from the connecting airport to the arrival at the destination airport. Depending on the replaced flight, only the filed flight time of the first flight leg t^{FFT1} or second flight leg t^{FFT2} remain. The intermodal connecting time t^{IMCT} is added since the transit arrives early for feedrail and departs later for endrail.

For allrail and bypassrail, t^{GT} forms the entire journey travel time. This is because the traveller takes no flights and hence it is assumed no extra time is needed to access or egress the airport. For feedrail, the average door-to-kerb time is not added. This is because it is assumed the traveller takes a train directly from their origin door to the connecting airport of the normal MSF. And for endrail, it is assumed that the traveller goes directly to the destination door, hence saving on the kerb-to-door time.

To calculate the extra travel time, the intermodal travel time was subtracted from the travel time of a normal MSF. A normal MSF consists of all the airport access and egress times, both filed flight times and the transfer time. Now consider the case of an allrail MSF not being replaceable, i.e. the extra travel time an intermodal passenger has to travel versus the MSF alternative is larger than the predetermined extra time of 60 minutes. If allrail is not replaceable it is reverted to a feedrail category. If the feedrail cannot be replaced either, it is then placed into endrail. Because feedrail and endrail MSFs were derived from allrail, the MSFs have to be deduplicated. To remove the unwanted duplicates, a priority list is made where only the first instance found is kept. Replaceable allrail MSFs were at the top, followed by feedrail, then endrail (including derivatives from allrail), followed by non-replaceable MSFs in the same order.

IV. Estimating Carbon Dioxide Emissions

A. Carbon Dioxide Emissions from Flights

In order to calculate the carbon dioxide emissions, a model which considers distance and aircraft type was desired. The FEAT model, published in a study by Seymour et al. [13], fit these criteria and contains fuel burn models for all but a few aircraft models within the flight data. Aircraft models not in the FEAT model were mapped to other similar or competitor aircraft. The FEAT model was used to calculate the fuel burn in kilograms of a flight as shown in Eq. 5.

$$F_i = \alpha_i \cdot d_g^2 + \beta_i \cdot d_g + \gamma_i \tag{5}$$

Where F_i is the fuel burn of a flight in kilograms. The parameters α_i, β_i, γ_i are aircraft-type specific parameters derived from the FEAT model study [13]. Finally, d_g is the great circle distance between airport pairs given in Eq. 1.

The fuel burn was converted into well-to-wheel (WTW) and life-cycle assessment (LCA) carbon dioxide emission factors given in Eq. 6 and Eq. 7, respectively. These factors were divided by the number of passengers on the flight to get the emissions per passenger. The proportion of freight versus passengers was factored out to not attribute all the emissions to passengers.

$$WTW_f = F_i \cdot PF \cdot (EF + P) + AF \cdot x + A \tag{6}$$

$$LCA_f = WTW_f + AF \cdot x + A \tag{7}$$

Where WTW_f and LCA_f are the well-to-wheel and life-cycle assessment emissions per passenger for a flight in $kgCO_2e$, respectively. PF is the worldwide passenger freight fraction of 85.1% [13]. EF is the CO_2 emissions factor for jet fuel combustion or tank-to-wheel emissions, equal to 3.16 kilograms of CO_2 produced by burning one kilogram of aviation fuel [14]. P is the well-to-tank (WTT) emissions factor of 0.538 CO_2 kg/kg calculated in Messmer and Frischknecht [15]. AF is the aircraft production, maintenance and disposal factor 0.00038 kgCO_2e/paxkm, as estimated in Messmer and Frischknecht [15]. x is the actual flight distance flown in kilometers. Finally, A is the airport infrastructure and operations emissions 11.68 kgCO_2e/pax, as estimated in Messmer and Frischknecht [15].

B. Ground Transportation Carbon Dioxide Emissions

Ground transportation emissions were calculated both using a WTW and LCA perspective. This way, carbon dioxide emissions from flights can be directly compared to the intermodal alternative.

The Google Maps API contains many different vehicle types, all from many different countries. Average emission factors for different vehicle types, including high-speed rail (HSR) and non-high-speed rail (NHSR), were used to calculate the carbon dioxide emissions per passenger for each kilometer travelled. These emission factors are given in Table III and were multiplied by the distance travelled to calculate the emissions for each step in the journey. This was then summed to obtain the total journey's carbon dioxide emissions per passenger.

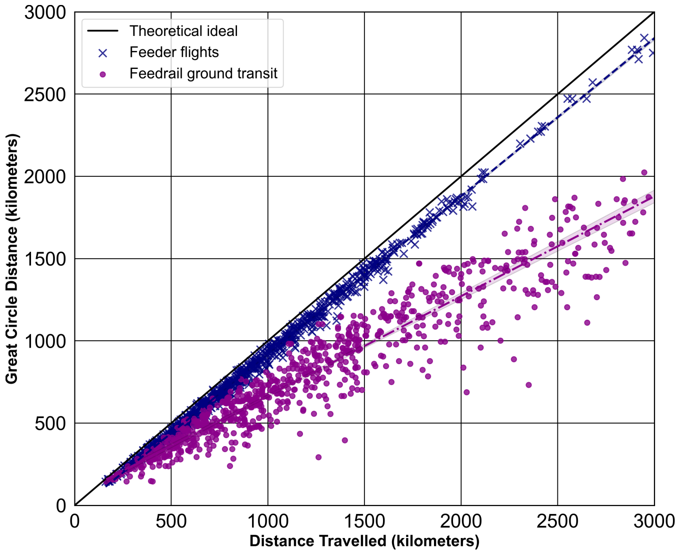


Fig. 4: Theoretical versus actual distance travelled for feeder flights and transit with 95% confidence intervals.

Vehicle type	WTW ($\frac{gCO_2e}{pax \cdot km}$)	LCA ($\frac{gCO_2e}{pax \cdot km}$)	Source
Bus	94.27	105.27	[16, 17, 18]
Intercity bus	58.57	69.57	[16, 17, 18]
NHSR	27.36	32.65	[19, 20, 21, 22, 19, 23, 16, 24, 25]
HSR	19.04	38.78	[26, 27, 19, 28, 29, 30, 25]
Light rail	84.2	95.2	[16, 17]

TABLE III: Ground transportation well-to-wheel (WTW) and life-cycle assessment (LCA) emission factors averaged for Europe, given in grams of carbon dioxide equivalent per passenger (pax) kilometer (km).

The emission rates per kilometer for ground transportation are generally much lower than for flights. However, the transit network is less efficient in taking the direct route than flights. This can be seen in a comparison made in Figure 4 between the theoretical versus the actual distance travelled. Hence, it is important to look at the complete journey to understand the emissions reduction per passenger.

To improve the WTT estimation of rail transportation, country-specific electricity generation emissions factors were used to adjust the WTT emissions per country [31]. The country-specific factor was the ratio between the country's electricity generation emissions divided by the average European Union plus United Kingdom electricity generation emissions. To do this, the coordinates per step per country were needed. The Google Maps API response contains a polyline string, which was decoded using the polyline python package [32]. This decoded polyline string gives a list of coordinates of the entire step. These coordinates were reverse geocoded using the reverse geocode python package [33] to retrieve coordinates per country as a dictionary. The resulting resolution between each coordinate was less than one meter.

Many rail operators do not specify that their train is a high-speed train, hence two conditions were made to post-process the data. If the average speed of a step is more than 150 km/h, or if the vehicle name provided contains any of the acronyms of high-speed trains in Europe, the train would be considered a high-speed train. The average speed was chosen to be much lower than the average maximum speed of high-speed rail which is about 300 km/h. This was done because the number of stops, transfer times and certified speed causes the average speed to be lower.

For NHSR, various sources are given in Table III which were used to calculate the average WTW and LCA factors across Europe. If a study only considered infrastructure emissions, the average WTW emissions were added to them to arrive at an LCA emission before averaging. This was done because the rolling stock is a very small portion of the additional LCA emissions for trains, hence it is negligible. The final difference between WTW and LCA emission averages for NHSR is in accordance with the official figure from Prussi and Lonza [34], which suggests adding 5 gCO_2e/pkm to include infrastructure, maintenance and manufacturing carbon costs.

The same that was done for NHSR was done for HSR. HSR's infrastructure-related emissions factors vary widely per line with a range of 5.1-102.6 gCO_2e/pkm. HSR has a mean infrastructure cost of 29.03 gCO_2e/pkm and a median infstructure cost of 9.8 gCO_2e/pkm. This variation per line is because it depends on the annual volume of the line. In the case of the Basque Y line, this annual volume is an order of magnitude less than other lines, leading to the highest infrastructure cost of 102.6 gCO_2e/pkm [35]. There are two main reasons why HSR has a lower WTW factor than NHSR. Firstly, the load factor of HSR tends to be double that of NHSR. Secondly, HSR is mostly electric, whereas NHSR is 80% electric, and the rest are diesel-powered [36].

The emission factors for buses were calculated using the European Environment Agency [16] averages assuming a market share of 70% diesel busses and 30% alternative fuel busses to calculate the WTW emissions. The global WTW and LCA averages by the International Transport Forum [17] were used to calculate an additional LCA of 11 gCO_2e/pkm to the European WTW average. This assumes that the global additional LCA difference from rolling stock, maintenance, etc., is the same in Europe.

Finally, the WTW emission factors for light rail (subway, tram and metro) were the estimated emissions average from the European Environment Agency [16], and the global difference between LCA and WTW from International Transport Forum [17] was used to calculate the LCA of European light rail.

V. Model analysis

In this section, the environmental and travel time efficiency gains of intermodality are highlighted from a passenger's perspective. Then, the impact and areas of improvement for intermodality are considered. Finally, the model's output sensitivity to varying the input parameters is made.

A. The Efficient Intermodal Passenger

The intermodal passenger leverages different transportation modes to be most efficient in both travel time and carbon dioxide emissions. The extra travel time due to intermodality versus great circle distance (GCD) is visualized for different intermodal categories are shown in Figure 5, averaged per airport pair. For an extra travel time of 60 minutes, distances up to 500 km do not add considerable travel time for many feedrail or endrail intermodal journeys, and up to 1000 km for allrail.

Intermodality reduces the life-cycle assessment (LCA) emissions per passenger, as can be seen in Figure 6. It is clear that high-speed rail (HSR) LCA emissions exhibit a polynomial growth over distance, while flight emission increases remain linear. This is because the infrastructure costs for flights are

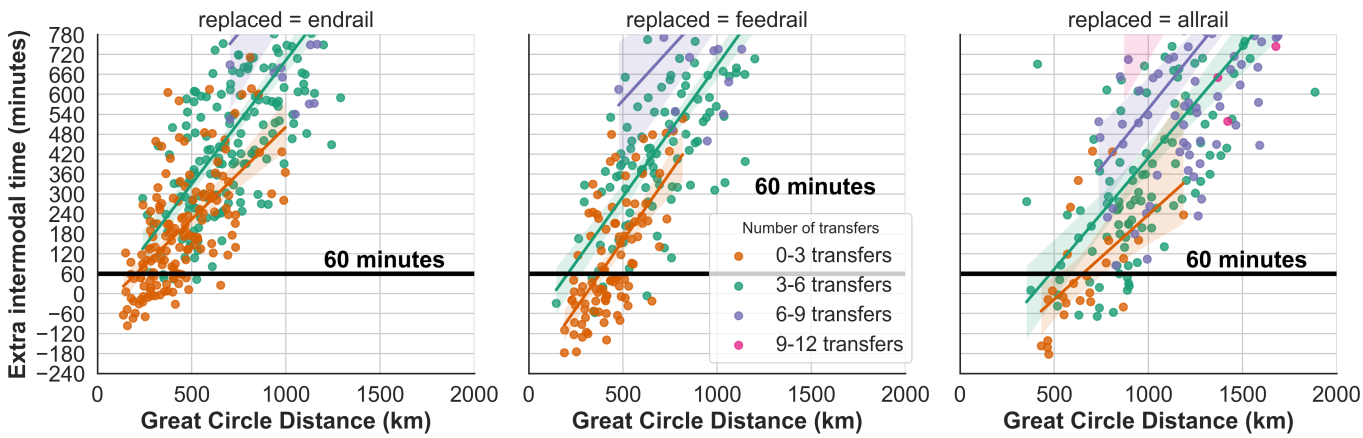
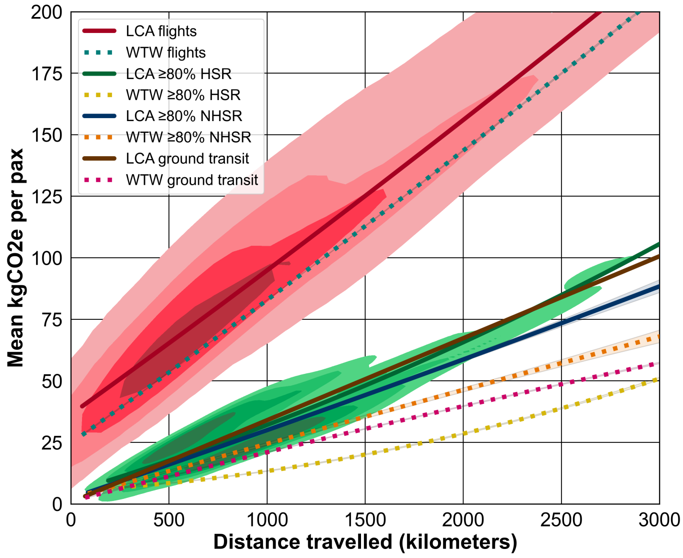
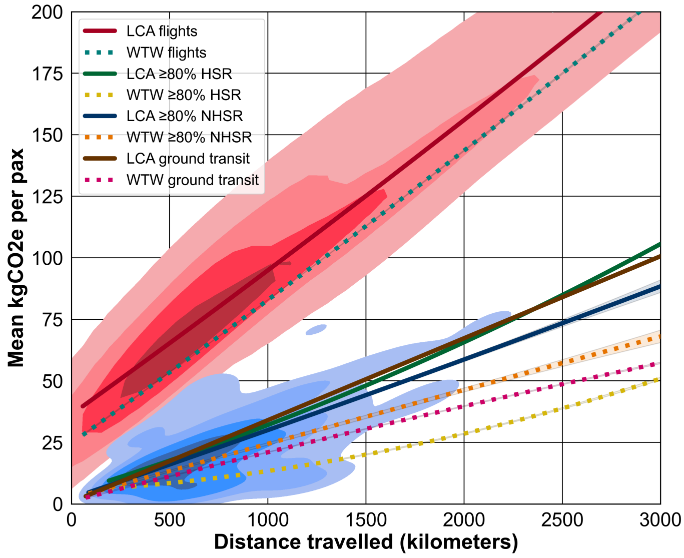


Fig. 5: GCD versus extra intermodal travel time for the top 1000 airport pairs in terms of total transfer passengers.



(a) High-speed rail (HSR) against flight CO_2 emissions.



(b) Non-high-speed rail (NHSR) against flight CO_2 emissions.

Fig. 6: Well-to-wheel and lifecycle assessment emissions of ground transportation modes and flights by distance. The 95% confidence intervals and kernel density estimation with 5 levels and 20% threshold are included.

constant, while for rail the infrastructure costs continue to increase over distance. For countries with low energy generation emission factors, such as Norway and France it is clear that ground transportation is a cleaner way to travel. For a distance of 1000 km, taking a flight would increase the passenger's carbon footprint on average by about 100 kgCO2e. While for ground transportation, this average is about 30 kgCO2e. There is a much wider range of possible emissions for ground transportation. Hence, the saved emissions can range at times from about two-thirds to only about one-half. Non-high-speed rail (NHSR) has a larger range of values compared to HSR, however, the LCA average is quite similar to HSR. HSR is a good option against NHSR up to 1000 km distance if comparing it from an LCA perspective. This is contrary to the expected higher emissions of HSR versus NHSR because of the high infrastructure costs [37]. This is because as mentioned in Section IV-B, HSR has high load factors. Also, HSR is mostly present in countries with (below) average electricity generation emissions factor.

The sustainable intermodal passenger would do a trade-off between time and emissions saved to come to a choice. The model takes into account all the different route emissions, hence it allows passengers to make the right choice. In the bigger picture, it also allows the actual impact of a modal shift to be visible as it has a granular view of each route's differences throughout the day.

Further emission savings from reduced delays and airport operations would be interesting future work. Lubig et al. [38] found that hub airports operating at capacity limits have downstream effects on the hub airlines' operation performance. A simulation illustrates this effect, increasing capacity by 10% at London Heathrow improves the rate of successful flight connections from British Airways by 10% and decreases the in and outbound delay at London Heathrow by 42% and 80%. Current hubs are already facing capacity constraints due to congestion [39].

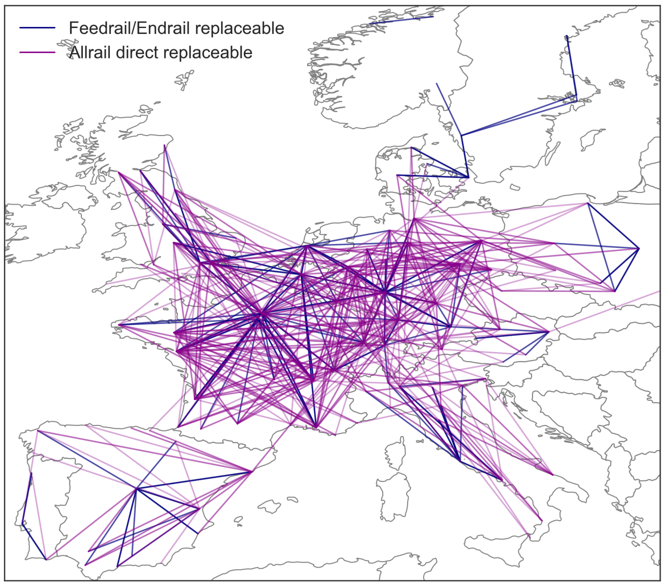


Fig. 7: Replaceable routes for 60 minutes extra travel time. Allrail (intra-European MSFs) is given in direct routes. Only routes with larger than 50% replaceability of MSFs are shown.

B. Intermodal Impact

The current impact of intermodality on MSFs can be seen in Figure 7 by considering the replaceability of MSFs in Europe. A large number of replaceable routes are available all over Europe. It is clear the hubs in Amsterdam, London, Paris, Frankfurt, Madrid, Zurich, Rome, Warsaw and Munich are intermodally well-connected and are capable to replace many

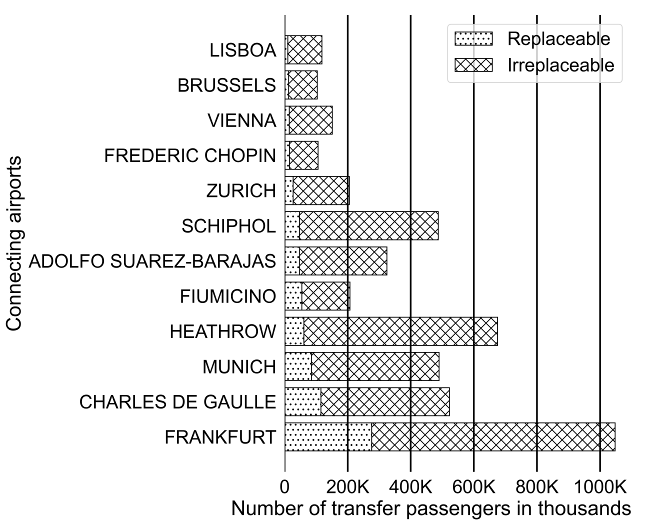


Fig. 8: Replaceable EU transfer passengers at hub airports for a maximum of 60 minutes of extra travel time.

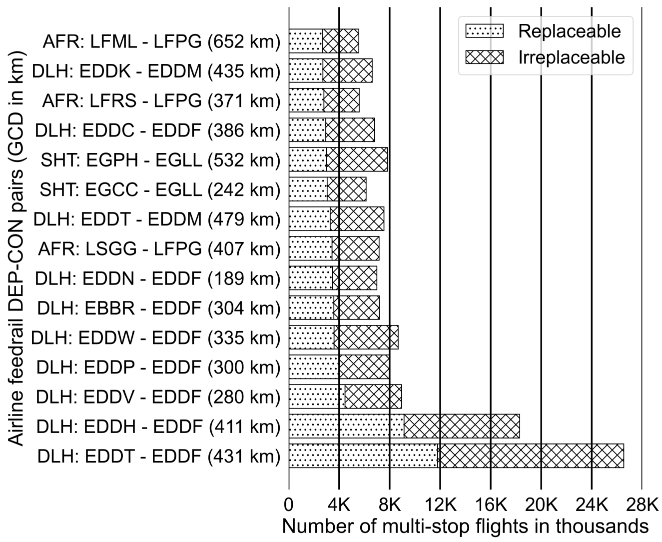


Fig. 9: Top 15 feedrail airline routes in terms of the number of replaceable MSFs for 60 minutes extra travel time.

feeder flights. The hubs show less replaceability for allrail. This is because hubs already have many direct flights and hence these routes were not deemed realistic MSF routes as explained in Section II-A. Better connections between Portugal and Spain, as well as between Germany and Austria could lead to higher intermodal efficiencies. Also, many intermodal efficiency gains can be made domestically.

Cross-border intermodal options are competitive in terms of travel time between the UK, France, Belgium, the Netherlands and Germany. In Figure 8 the number of replaceable transfer passengers is shown for the top intermodally efficient connecting airports. Reduction of flights in this area can lead to delay reductions in the busiest and most heavily delayed area control centres (ACCs) in Germany and France, such as Karlsruhe upper area control centre and Paris ACC [40]. Hub airports that are congested can benefit from a reduced number of transfer passengers. Over time a reduced number of flights would be seen, as airlines reduce the frequency of the flights due to lower demand and fewer connecting flights needed.

A view of the top feeder flight routes shown in Figure 9 also gives insight into the distance and replaceability of certain routes. Airlines and railway operators can use views such as these to gain insight into where to focus their efforts in a modal shift. Also, policymakers can use such a view to better understand which routes must be improved or can be utilized for intermodality. Lufthansa (DLH), and Air France (AFR) have plenty of intermodally efficient feeder flight routes that can be replaced with feedrail. Also, since many of these routes have (almost) 50% replaceability, the intermodal efficiency could be easily improved by improving coordination with transit as will soon be analyzed.

Another interesting view for airlines, railway operators and policymakers is the transfer passenger flow map given in Figure 10. This map allows for more insights into the passenger flow magnitude and replaceability. While the route map in Figure 7 shows also routes which have are quite insignificant in terms of transfer passenger numbers. In Figure

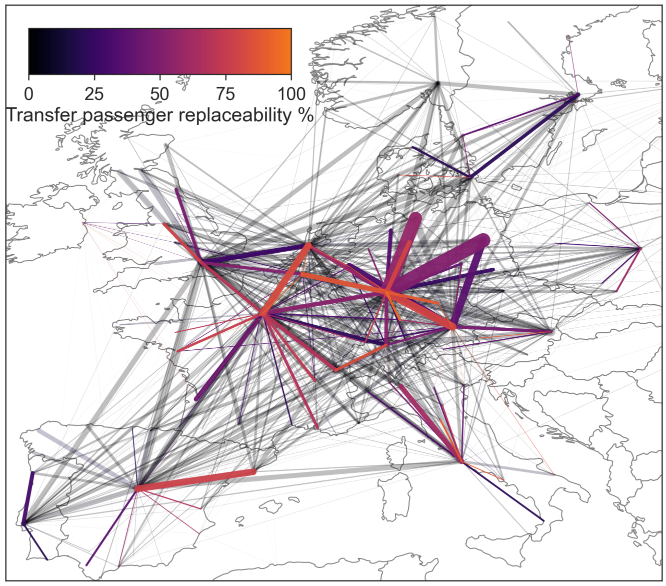
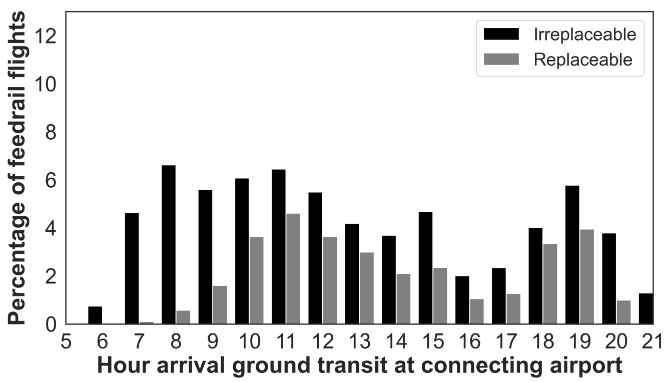


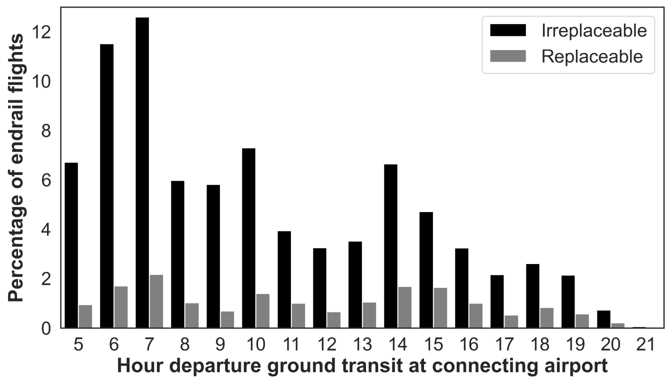
Fig. 10: Replaceable transfer passenger flows for 60 minutes extra travel time. The thickness of the lines represents the ratio to the total number of transfer passengers. Replaceability percentages below 20% are made translucent.

10, it can be seen which regional airports are redundant for intermodal passengers, i.e., a passenger might as well take ground transportation to arrive at the hub airport for feedrail or arrive at the final destination for endrail.

The time of day a flight arrives or departs has a strong influence on the replaceability of a MSF due to varying transit schedules and the number of transfers throughout the day. This effect can be seen in Figure 11. Airlines can improve their intermodal efficiency by placing feeder flights at times when transit is more effective. While these optimal times differ per region and day, a rule of thumb would be to place feeder flights departing between noon and 9 pm. This corresponds to a 10



(a) Feedrail ground transportation arrival time.



(b) Endrail ground transportation departure time.

Fig. 11: The arrival and departure times at the connecting airport for ground transportation compared to the replaceability of a MSF segment for 60 minutes extra travel time.

am arrival time using ground transit, which allows transit to be fully active. Moving flights later in the day would decrease the intermodal door-to-door travel times for about 20% of feedrail multi-stop flights (MSFs). For endrail, it is best if flights arrive after 8 am, which at the moment more than 30% of endrail flights arrive before 8 am.

In Table IV, selected output metrics for replaceable MSFs of the baseline model are shown for a varied number of maximum extra travel times. The total estimated transfer passengers in Europe for March 2019 by the model is 6 million. If all of them became intermodal, they would collectively save 361,000 tonnes of CO2. However, for a maximum of 60 minutes of extra travel time, 1 million transfer passengers would save 52,000 tonnes of CO2. Assuming each month of the year to be the same, this would lead to 624,000 tonnes of savings from transfer passengers alone. On average, 72% of the LCA emissions of the intermodal replaced segment would be saved, and about 30% of the total journey's LCA emissions.

C. Sensitivity of multi-stop flight model

The reconstruction of realistic MSFs was made with a number of conditions and assumptions which carry varying uncertainties, as was mentioned in Section II-A. In this section, a local sensitivity analysis was conducted on the model's input

Metrics \ Extra minutes	**0**	**60**	**120**	**180**
Saved D2D travel time (minutes)	66.82	28.21	-10.12	-43.49
Total Tonnes of CO_2e saved LCA	26,207	46,761	70,832	94,185
Segment kgCO_2e per multi-stop pax	75.25	76.76	78.89	82.05
Segment kgCO_2e per intermodal pax	18.93	20.42	21.91	23.62
pax replaced per MSF	2.6	2.9	3.1	3.2
Great circle distance (kilometers)	455.8	479.7	508.1	543.2
Number of transit transfers	2.41	2.59	2.78	2.97
Replaced transfer pax	553K	1001K	1510K	1962K

TABLE IV: Comparison between the metrics of replaced MSFs for varying extra intermodal door-to-door (D2D) travel time in March 2019. pax is used as a shorthand version for passenger(s). Mean values are used unless otherwise noted. A passenger is counted as replaced, i.e. intermodal, if their extra travel time is lower than the given extra minutes.

condition parameters to gain insight into its influence on the results. Also, a simulation of varying the airport transfer rate and airport transfer time was done to assess the uncertainty of passenger transfer flows.

The local sensitivity analysis led to the correlation matrix shown in Figure 12. It highlights the correlation of the varying input parameters, given in Table I, to the output metrics. Starting with the airport transfer time, it is clear that ensuring more time between flights would lead to less extra intermodal D2D travel time. This is because ground transportation does not need some layover time between flights, it only needs to arrive on time for the next flight in the case of feedrail or depart after landing at the connecting airport in the case of endrail. A larger transfer time, has a negative correlation with the total number of MSFs, especially for intra-European MSF combinations. This seems to suggest that intra-European MSFs are very well-optimized in connection time, and many transfers are possible right after landing.

For the sense condition, a particular effect happens to the intermodal D2D travel time. The intermodal travel time decreases as the switching point (total vs direct distance) to a horizontal line happens further away, see Eq. 4. Increasing this switch distance means more realistic MSFs but at further away distances. For allrail the short-haul sense condition is especially influential, leading to more allrail possibilities and replaceability as the more direct route is taken by ground transportation when the short sense condition value increases. Finally, the worth (maximum direct distance) condition logically has a negative correlation with the total number of flights. However, for the range of direct distances used, it seems that there are not many possible MSFs at these short distances.

Figure 13 shows the replaceability of feedrail, endrail and allrail when changing the model input parameter conditions. The other input parameters given in Table I have a small effect. The maximum direct flight frequency and maximum transfer

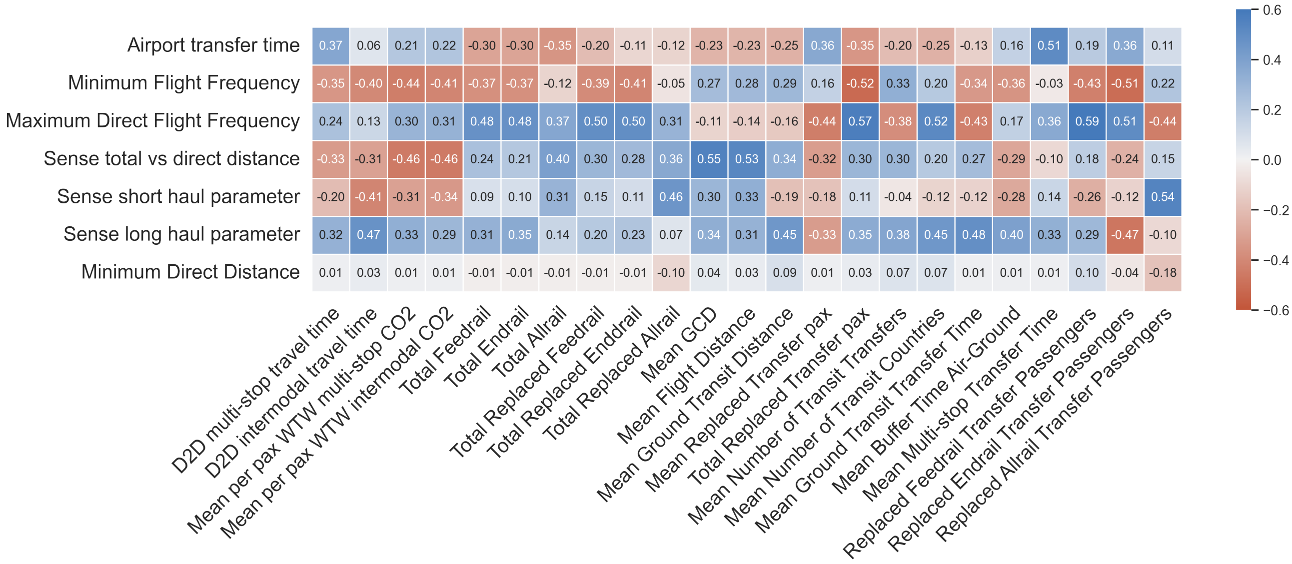


Fig. 12: Correlation matrix using Spearman's rank correlation coefficient from the sensitivity analysis on condition parameters for realistic MSF reconstruction. A positive correlation means, i.e., that as the airport transfer time input parameter is increased, that the door-to-door multi-stop travel time also increases.

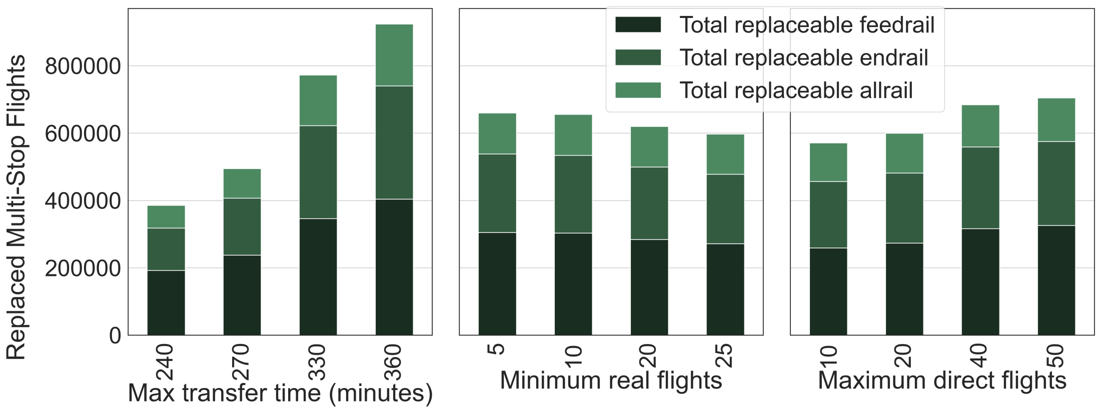


Fig. 13: Output sensitivity of the replaced MSFs depending on the input parameters.

time between MSFs are the greatest determinants of the output of the model. The minimum frequency of flights on both routes unnecessarily removes some viable MSFs and possible transfer passengers. Hence, this condition can be removed.

As explained earlier, more data is needed on pricing and passenger preferences to better identify realistic MSFs where many direct flights exist. However, the transfer passengers estimated by the model are not very sensitive. The total transfer passengers always lie within a range of 6 million to 6.5 million passengers, with a mean of 6.28 million passengers. Likewise, the number of replaced transfer passengers ranges from 965K to 1056K passengers, with a mean of 1 million. Hence, the model can be considered to produce outputs that are not extremely sensitive to the input parameters.

The correlation between the input parameters and output parameters of the simulation is given in Figure 14. While there exists a strong correlation between the parameters, the total replaced transfer passengers are not affected by more than 3%, at maximum. Even the airport transfer rate does not affect the outputs of transfer passengers, as adding or subtracting the uniform noise averages out after 100 runs.

VI. Discussion

In this section, the verification and limitations of the model are described and discussed with recommendations for improvement. Then, some insights into the future of European Mobility and Sustainability strategy are made. Finally, the different stakeholders are recommended certain actions derived from the insights of this paper.

A. Ground Transportation Model Limitations

The ground transportation data derived from the Google Maps API is dependent on transit operators uploading their schedules to the API service. Hence, not all schedules are available. This leads to less optimal and overall fewer routes. To bypass this limitation, future work can merge journey data from other providers such as Interrail [41], with permission.

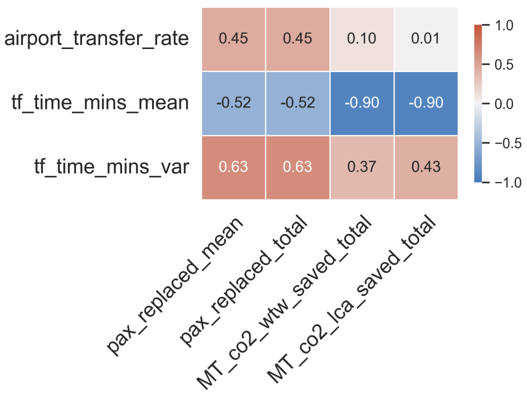


Fig. 14: Correlation matrix of the simulation using the Spearman method, highlighting the influence of the airport transfer rate and transfer distribution parameters on the passenger numbers and emissions.

Another limitation is that there are about 40,000 requests available for free per month from the Google Maps API at the time of writing. This led to grouping flights to 'route timeslots' of 1 hour to reduce the number of requests. Also, only route timeslots with at least 30 multi-stop flights (MSFs) and those routes that have a Haversine distance of more than 2500 kilometers were kept. Timeslots of 30 minutes or 15 minutes instead of one hour could be used to reduce the ground-to-air transfer time and find optimal journeys for a more specific arrival/departure time. Also, removing the constraints on the minimum number of flights and maximum distance in a route timeslot can lead to more replaced possibilities.

Choosing the fastest of each of the alternatives within a route timeslot given by the API resulted in overall better performance of the intermodal journeys. However, it does cause the possibility of a journey to be a bit slower. This is the case if the 'faster' ground transportation journey departed much later (in the case of endrail), or arrived much earlier (in the case of feedrail) than when the switch to air transportation occurs. Smaller timeslots could reduce this effect to become negligible.

The transfer passenger model assumes the transfer passengers can be shifted to transit without looking at transit maximum capacities. Since the origin of feedrail, or the destination for endrail replaced transfer passengers differ, the only common shared transit option would be a train from or to the airport. Consider the edge case where all transfer passengers spend at most 1 hour extra to travel intermodally. In this edge case, there might be about 400 passengers replaced at any given time combined between all replaced categories. This occurred for the route EDDT-EDDF, at 5 am and at 6 pm. International trains such as Deutsche Bahn's ICE for which many of these edge cases lie have capacities of 800 plus passengers [42]. Hence, transit capacity should not be a problem for accommodating transfer passengers.

Finally, the carbon dioxide emission factors for ground transportation are difficult to estimate. It depends on many factors including the load factor of the vehicle, the number of stops, its energy source, the annual volume of the line, etc.

Metric	Intermodal Model	Schiphol Unfiltered	Model Fraction
Air Transport movements	26,372	39,785	0.66
Air Transport movements Europe	21,959	32,070	0.68
Air Transport movements intercontinental	4,413	7,715	0.57
Transfer passengers	1,217,658	2,059,198	0.59
Passengers total	4,428,666	5,630,314	0.79
Passengers Europe	3,243,321	3,947,789	0.82
Passengers intercontinental	1,185,344	1,682,525	0.70
Pax per flight	168	142	1.18
Pax per Europe flight	148	123	1.20
Pax per intercontinental flight	269	218	1.23

TABLE V: Schiphol official figures for March 2019 [43] and the intermodal model's intermodal air traffic and passenger numbers. Schiphol numbers include low-cost flights and extra-EU transfer passengers, which are filtered by the intermodal model.

Future work is necessary for improving the estimate, especially considering infrastructure emissions per high-speed line. This is because each line has different traffic volumes leading to large differences in infrastructure costs.

B. *Multi-stop Flights Model Verification*

To further improve the MSF reconstruction, the airline alliance data can be enhanced with codesharing agreements among individual airlines and other smaller alliances. Regarding the minimum connecting time, it would be interesting to include data such as whether the passenger arrives at an EU airport from an EU airport, the hour of the day, the distance between the gates (usually unknown), and the total number of passengers in the aircraft can be used to create a better connecting time approximation. Also, adding another condition to keep MSFs realistic if there are many direct flights but also many MSF possibilities would improve the reconstruction. This is because hub-and-spoke airlines with high operational density can outprice direct flights significantly at times. Passengers then trade off the cheaper MSF albeit for less convenience and a longer travel time.

Aircraft were filled with passengers using only the high-density configuration, as mentioned in Section II-B. This was done due to the uncertainty of seating classes per airline. This leads to underestimating the carbon dioxide emissions per passenger on each flight, and also overestimating the number of passengers. Hence the number of transfer passengers is also overestimated. As a sanity check, Schiphol's monthly data containing transfer passenger numbers were used to understand the differences between the intermodal model with the official air traffic figures [43]. This comparison is given in Table V. Note that due to the international counting method, transfer passengers are counted double.

Firstly, low-cost airline flights were removed from the flight data. This contributes to the decrease in air transport movements for the model and also led to transfer passengers using low-cost airlines not being included. KLM for example works with Transavia, a low-cost airline, to increase their connections, which leads to a MSF from Zurich to Amsterdam to Sevilla.

Secondly, the MSF reconstruction model removes MSFs where there are not at least 2 airports within the area of interest shown in Figure 1. As Schiphol is an international hub, many transfer passengers hop over at Schiphol and continue their journey outside of the area of interest in this paper. This number is not given in the figures which leave an unknown of what percentage of transfer passengers are only hopping over in Europe.

Thirdly, the baseline initial parameters for the MSF model might be too strict. By reducing the number of MSFs to work with, the number of transfer passengers is directly affected. Especially, the maximum airport transfer time and the maximum number of direct flights have a huge influence on the results as was analyzed in Section V-C. Also, Schiphol considers transfer passengers within a 24-hour window, not a maximum of 5 hours of transfer time as this paper uses.

Finally, the passenger load factor for Schiphol was 85% in 2019. This is above the worldwide average used, leading to an underestimate of the number of passengers. This difference in load factor is likely due to the higher load factor of international flights.

To remedy the limitations four suggestions are made. The passenger load factor for domestic and international routes should be varied according to actual route load factors given by ICAO [44]. Secondly, the data cleaning must be revised to ensure commercial passenger flights are not unnecessarily removed. Thirdly, the aircraft seat configurations should be added to have a finer estimation of the passengers. Finally, airline codesharing agreements should be added, and low-cost airlines should be kept in the flight data.

For aviation emission estimations, various online calculators exist [44, 45]. These were used to compare the FEAT model's predicted CO_2 emissions with their estimations and to understand where the model is limited and the differences in calculations. This comparison is given in Table VI. The well-to-wheel (WTW) emissions of the model are compared to the tank-to-wheel (TTW) emissions given by ICAO [44]. As the WTW emissions include the TTW emissions, the FEAT model underestimated the per-passenger emissions for regional flights due to the load factor of regional flights being overestimated. At the same time, the per-passenger emissions for international flights were overestimated because the load factor was underestimated. The fuel burn in general is underestimated, this might be due to a difference in the distribution of aircraft types. The life-cycle assessment (LCA) of the myclimate calculator includes a radiative forcing index multiplier that doubles the emissions [45]. Future work could improve the model by including a radiative forcing index for flights depending on e.g. the flight level at cruise.

Parameter \ Route	EHAM-EGLL	EHAM-LEMD	EHAM-KJFK	EDDH-EDDF
Model fuel burn (kg)	2328	6547	41217	2654
ICAO fuel burn (kg)	2552	7455	44597	3156
Model WTW kgCO2e/pax	48.2	113	401	44
ICAO TTW kgCO2/pax	59.8	127	311	58
model LCA kgCO2e/pax	60	126	415	56
myclimate LCA kgCO2e/pax	130	274	949	136

TABLE VI: CO_2 comparison between the model and online calculators [44, 45] for different routes.

C. *Intermodal Journey Revisited*

In this paper, the door-to-door journeys always start and end at airports. This was done to simplify the model and not exceed the API request limitation. However, this mostly overestimates the ground transportation time, as passengers tend to start or end their journeys in cities. Of course, air traffic management (ATM) consultants on business trips perhaps do save time as their final destination is the airport. Since cities tend to be better connected than airports, future work could look at complete door-to-door journeys with mean travel times from major popular centres, for instance. For this reason, an extra travel time of 60 minutes was chosen as the main method to compare the intermodal alternative, as it typically takes around 30 minutes to travel between the airport and the city, according to Innaxis [12].

To validate the travel times, the mean travel times were compared to the DATASET2050 study, which contains gate-to-gate (G2G) and door-to-door (D2D) times for non-stop and 1-stop MSFs. 1-stop MSFs are journeys with 2 flight legs, which the model in this paper recreates. For individual single flights, the data used in this paper suggests lower average gate-to-gate times (87%) and door-to-door (89%) times than the DATASET2050 model. This occurs even after adding the deboarding time assumed of 10 minutes and adding the 15 minutes extra before departure buffer. A possible explanation for this is that DATASET2050 includes delays (months with much congestion), and uses different deboarding times and different departure buffers. In contrast, for MSFs, the model presented in this paper calculates a higher average D2D (105%) and G2G (106%) times than the DATASET2050 simulations. This could be because real data was not used in the DATASET2050 study, but rather an educated approximation of the transfer times, perhaps idealized to the hub airport's advertised minimum connecting times of 30 or 45 minutes and adding some deboarding and departure time buffer.

D. *Future European Mobility and Sustainability Insights*

The European Union is investing heavily in e.g., high-speed rail infrastructure, improving transit connections and shifting air passengers to rail passengers. Over time, these developments will further make the case for intermodal transportation more attractive. However, this paper shows that the best day to start is *today*, as many passengers can already make benefit from intermodality, leading to fewer emissions from aviation.

Air traffic will continue to grow as the world population grows or economic prosperity increases. Future technological innovations such as electric aircraft and hydrogen aircraft aim to reduce the environmental burden that this air traffic growth will bring with it. These innovative aircraft do not produce carbon dioxide emissions during operation, however, the well-to-tank and life-cycle assessment emissions must be taken into account for a more holistic view. For instance, the production of electricity, and transportation, production and storage of gaseous/liquid hydrogen. Likewise, high-speed rail's environmental impact due to infrastructure construction has to be looked at more closely per line to justify new projects.

Europe wants to decrease door-to-door travel time under the Flightpath 2050 vision, and travellers prefer faster travel. Hence, high-speed rail is sometimes a necessity for a modal shift from air to ground to occur. This modal shift enabled by travel time competitiveness with low transfer times and seamless air-ground transfers increases the rail traffic density and volume of existing and future lines. This would reduce the high years required for climate compensation of some high-speed lines.

Why is aviation sustainability improvements *alone* not the answer? Contemporary aircraft will continue to share the airspace with these hydrogen and electric aircraft newcomers. Due to physics, these revolutionary aircraft will have much less passenger capacity than contemporary aircraft, hence leading to an even busier airspace. One challenge that has to be addressed is how to avoid extra flight inefficiencies of contemporary aircraft as the delays due to congestion will worsen. Another challenge is how the current ATM will manage such busy airspace, as air traffic controllers already have a high workload. Automation aims to help solve these capacity issues, but the safety concerns of when automation fails remain, and make technological adoption drawn out.

E. Recommendations to Stakeholders

Recommendations to Air Travellers

Air travellers considered in this paper are transfer passengers of MSFs consisting of two flights. These transfer passengers either start or end their journey in Europe and can replace one or both flights by ground transportation.

As an air traveller, one should compare the door-to-door travel times of multi-stop flights and the intermodal alternative. This paper found that many transfer passengers can decrease their total journey time. One should be aware that airlines advertise only flight times, which do not include layover times, or airport access and egress times.

For sustainable travellers, the carbon footprint reduction of the total journey can be reduced by at least half by using intermodality. Passengers fill up a flight. If there are fewer passengers in a flight because the transfer passengers became intermodal, airlines would decrease the frequency of flights on this route or use smaller aircraft. Hence, improving aviation's sustainability.

Recommendations to the Railway Industry

Passengers prioritize travel time. One should market to transfer passengers the time savings that are possible for routes which are intermodally efficient. One should also work with airlines to bring single tickets and assurances to passengers.

To increase the market share of rail versus flights, railway operators should focus on a couple of points. Firsly, one should improve the schedule coordination between (international) transfers. This is one aspect that should be done by analyzing routes where connections can be improved, especially where many transfer passengers currently take short-haul flights between the 500 and 1000 km range. However, distances much higher than this can be served for passengers taking intra-European MSFs. These air travellers can save time by not entering an airport and not having to wait the layover time. Also, one should reduce the number of transfers, or the number of stops, or have other direct train alternatives for the aforementioned routes. Regarding sustainability, one should work with the infrastructure provider to provide a clean energy mix to improve the sustainability of the electricity mix. Also, one should electrify diesel trains. Finally, one should increase the frequency of trains for high-demand feeder flight routes, and decrease prices to be more competitive with feeder flights.

Recommendations to the Aviation Industry

Airlines should cooperate with railway operators to improve passenger experience and better coordinate flight times to correspond to transit. Replacing short-haul flights with feedrail would also improve the overall profit margin. Short-haul flights are of lower margin, as they have a low load factor. This is because they must fly frequently and to many different spoke airport destinations to decrease the layover times for transfer passengers and offer connectivity. This reduction can be made into integration with feeder rail to maintain the feeding of passengers into highly optimized hub airport operations for long-distance flights.

Hub airports that are efficiently connected by rail, should offer airlines the opportunity to be intermodal. This would reduce the number of transfer passengers for the airport, while also increasing the number of passengers entering and leaving an airport. Intermodal hub airport operations should be prepared to handle more passengers for check-in, and security.

ATM organizations such as EUROCONTROL and local air navigation service providers should take a closer look at the environmental and operational efficiency gains of intermodality. One potential benefit is reduced congestion around busy area control centres. Sector and trajectory optimization studies considering the reduction of feeder flights due to intermodality should be conducted, among others.

Recommendations to Policymakers

One should invest in improving intermodality to ensure future connectivity. Gelhausen et al. [46] expects that almost 50 million and more than 250 million passengers will not be accommodated in 2030 and 2040 worldwide, respectively. This is despite mitigation measures such as increasing airport capacity and utilization, as well as increasing larger aircraft over time to carry more passengers per flight.

For sustainability studies, it is important to compare lifecycle emissions when assessing carbon dioxide emissions from vehicles, not solely the emissions from the combustion of fuel or the production of electricity. Also, one should collect data on annual passenger volumes for railway lines to allow the estimation of infrastructure emission costs. Furthermore, one should make it easier for companies and researchers to obtain carbon emission estimates for Europe from one up-to-date source on emissions for every country and for every vehicle type, with the distribution of vehicles within a category. This would also improve the consistency of studies and comparisons. One should avoid subsidising the construction of (high-speed) railway lines where there is not enough volume for it from a modal shift, leading to the environmental impact due to infrastructure construction not being recovered. Finally, one should subsidize clean energy to reduce electricity generation emissions. This electricity powers trains and eventually hydrogen or electric aircraft.

Airlines currently profit from the high operational density of hubs to offer cheap MSFs. Actions should be taken to make it cost-prohibitive for airlines to offer MSFs when an intermodal alternative for a segment of the air journey can be made in the same reasonable amount of time. One should implement, for instance, a fuel tax for domestic flights and intra-European short-distance cross-border flights. Incentives should be made to cooperate with railway operators where feeder flights can be reasonably replaced. Another point is that airlines only show the in-vehicle time, which for short-haul flights is usually much less than the total door-to-door time. This makes it difficult for passengers to make informed decisions. Hence, one should force airlines to include average door-to-door travel times for the departure and destination, including airport specific access and egress times.

VII. Conclusions and Future Work

The integration of transit into a multi-stop flight was analyzed to understand the impact of intermodality on door-to-door travel time and carbon dioxide emissions. For this purpose, a method to reconstruct realistic multi-stop flights from individual flight data was made. This was achieved by considering some logical assumptions of how air travellers choose multi-stop flights. These multi-stop flights were then used to estimate the number of transfer passengers passing through a connecting airport to specific European destinations. Actual transit data was used to replace a specific flight leg within Europe, integrating it within an intermodal journey. The total carbon dioxide emissions per passenger were estimated both from a well-to-wheel and a life-cycle assessment perspective.

The fundamental insight this paper has shown is that intermodal passenger travel can work *today*. Some findings from the application of the model for March 2019 show that 9% of transfer passengers can skip the feeder flight without any extra door-to-door travel time, leading to a 30% reduction of their total trip's LCA emissions. 550,000 transfer passengers could have been intermodal passengers, without sacrificing travel time, and they would have collectively saved a total of 29,000 tonnes of CO2. Especially domestic flights within Germany, France, Spain, and Italy have a high potential for efficient intermodality. The same can be said for cross-border connections between the UK, Germany, France, Belgium and the Netherlands.

The work presented in this paper could be extended to create what-if scenarios for future aviation and rail operations. Some examples include passenger flow analysis, travel time and emission comparisons, modal shift studies, etc. Follow-up studies can also look at improving the model's limitations by adding more sources of data, such as pricing data, to enable more realistic multi-stop flight reconstruction. Finally, the data-driven methodology can be extended on direct flights. Combined with the current work, this can enable a complete view of the total impact of intermodality.

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Part II

Preliminary Report (Previously graded for AE4020)

Synopsis

The impact of aviation on sustainability needs to be reduced while maintaining a similar total travel time for passengers. With more passengers flying each and every year, a reduction in the number of short-haul flights will reduce capacity constraints, reduce delays due to congestion, and aviation's climate emissions. Integration of ground transportation with multi-stop flights is an attractive combination to enable multimodality which can improve door-to-door travel times and reduce flights. Due to the hub-and-spoke model, passengers are required to wait for a transfer flight, which adds to the number of small short-haul flights and increases the emissions for traveling. Europe is a prime example where existing rail could be integrated with air transportation as it has an extensively developed railway network and short distances between major cities.

The literature review confirmed the hub airport congestion issues. Aviation needs to become leaner by trimming down short-haul flights that can be replaced by rail while maintaining connectivity. Competition and cooperation effects of air with rail both agree that rail entry reduces air traffic. Short-haul flights up to 800 km appear to be replaceable by rail without extra travel time. This range constitutes more than 50% of flights within Europe. Life cycle assessments reveal the hidden costs of high-speed rail construction and to offset these embedded emissions aircraft seats must turn into rail seats. Many methods to estimate ground transportation and air emissions are found which will be adapted to find the carbon emissions in the final report.

The main thesis objective is: "To assess the carbon emissions saved through achieving air-rail intermodal transportation of multi-stop flights by a data-driven method to the existing commercial passenger air and rail transportation system in Europe whilst not exceeding a predetermined increase in total travel time."

The method to reconstruct realistic multi-stop flights consisting of 2 flight legs were created, and the number of multi-stop passengers can be estimated with different strategies. Ground transportation is integrated with the time constraints of different replacement categories of multi-stop flights. Current limitations are that train capacity is not incorporated in the model. Figure 1 shows that air-rail intermodal integration can reduce travel times for distances up to 2000 kilometers. Clearly, air-rail intermodality supports the Flightpath 2050 goals and the European green deal initiative.

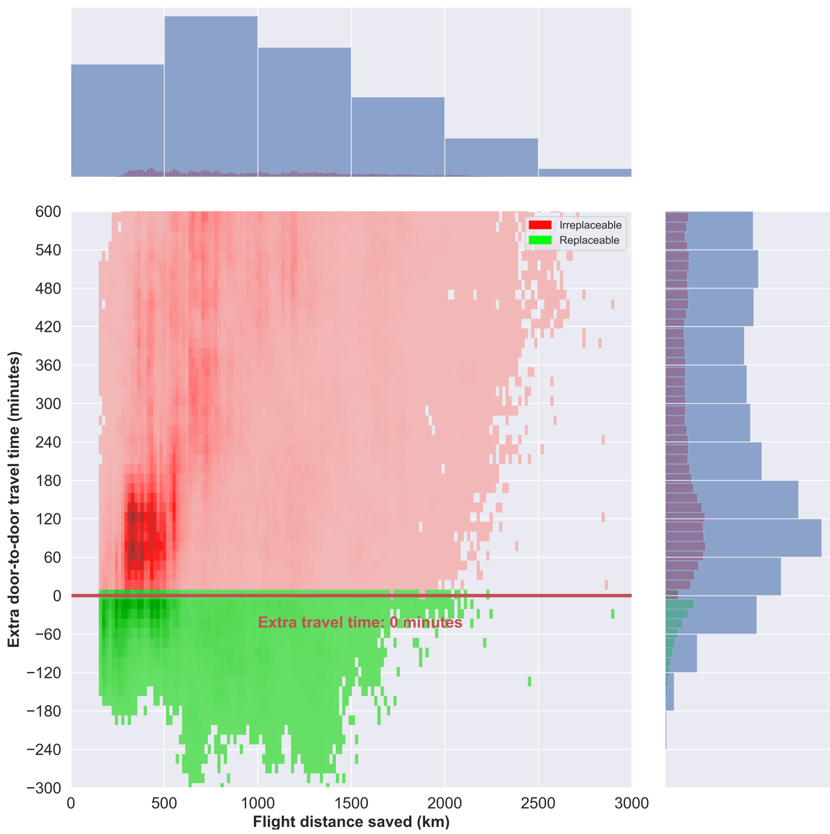


Figure 1: Actual distance flown and extra travel time for 0 minutes extra travel time.

1 Introduction

For over 100 years, human beings have been taking scheduled commercial flights (Sharp 2022). With a population increase of 25% to about 10 billion people by 2050 according to the UN (2017) and globalization increasing many challenges but also opportunities are presented to enable mobility for all. Air travel's societal benefits of flying should continue to grow but not at the expense of the environment. A shift to an intermodal traveling experience to include ground transportation as part of an air journey can reduce unnecessary environmental impact and enable future connectivity growth.

Air travel is currently returning to pre-COVID levels surpassing the most favorable models. With the increase in global population and economic welfare, the number of passengers will increase to more than 12 billion passengers worldwide by 2050 considering the estimated loss of 2-3 years of growth due to COVID (IATA 2022b; IATA 2021). More passengers mean more flight movements to about 16 million flights in Europe alone up 44% from 2019 which will further increase congestion and aviation emissions (EUROCONTROL 2022a).

Airlines currently use the hub-and-spoke model to maximize the number of people possible in a flight by using (short-haul, i.e. short-distance) feeder flights from the small-spoke airports to the larger hub airports. This leads to the most profit for airlines and also lower costs to passengers. From the passenger perspective, this lower cost comes at an increase in their total travel time as they must wait for their connecting flight at the hub. Also, feeder flights add to the congestion problems many hub airports are facing. Since feeder flights are necessary to increase the load factor of longer-distance flights, a way to circumvent feeder flights would decrease the number of flights while maintaining connectivity. Intermodal solutions combine different modes of travel for a complete door-to-door journey and are an interesting approach to solving capacity issues while improving travel times, in some cases, and in reducing environmental impact.

A data-driven approach is used to answer the research question: "What is the difference in carbon emissions between multi-stop air travelers and air-rail intermodal travelers originating from or traveling towards Europe in 2019, whilst not exceeding a one-hour increase in door-to-door travel time?"

Intermodality may lead to less air traffic leading to less congestion at airports. The delay decreases as the airport's capacity increases and leads to increased aviation environmental performance. Also since the number of flights is reduced, so is aviation's impact on the climate. The total travel time may decrease as travelers save on the transfer time. These intermodal solutions are becoming more prevalent as the HSR network extends over time, and airlines see the benefits in cooperation (Deutsche Bahn 2022; Air France 2022; Star Alliance 2022).

In this preliminary report the work conducted thus far and the literature review will be presented. The structure of the report follows. In chapter 2 the research framework, research objective, research question, and its relevant sub-questions are outlined. A literature review will be conducted in chapter 3 on 3 topics covering growth congestion, integration effects, and sustainability effects. In chapter 4, the methodology used to perform this research is explained together with the preliminary results of the algorithms implemented to achieve the research goals. In chapter 5, the preliminary analysis is presented. In chapter 6, the research framework is converted to show the current progress and next steps. A Gantt chart is also used to show detailed project planning. Finally, in chapter 7, the conclusion of this preliminary report is presented.

2
Research

In chapter 1, the main problems this research aims to solve are given. In this chapter the research framework to solve these problems and give a scientific approach to answering the research question is given.

2.1. Research Question

The main research questions and sub-questions to be solved are:

- What is the difference in carbon emissions for air travelers on multi-stop flights using air-rail intermodal transport versus only air transportation in Europe, whilst not exceeding a predetermined increase in door-to-door travel time?
  - To what extent is rail transportation a better alternative in terms of carbon dioxide emissions when compared to air travel?
  - To what extent is rail transportation competitive to air travel in terms of travel time from a door-to-door passenger perspective?
  - What are the possible environmental and operational efficiency gains by integrating air and rail in Europe for airlines, airports, and rail operators?
  - How can air-rail intermodal transportation contribute to the high-level European mobility and sustainability goals?

2.2. Research Objective

The main research objective of this thesis is:

> To assess the carbon emissions saved through achieving air-rail intermodal transportation of multi-stop flights by a data-driven method to the existing commercial passenger air and rail transportation system in Europe whilst not exceeding a predetermined increase in total travel time.

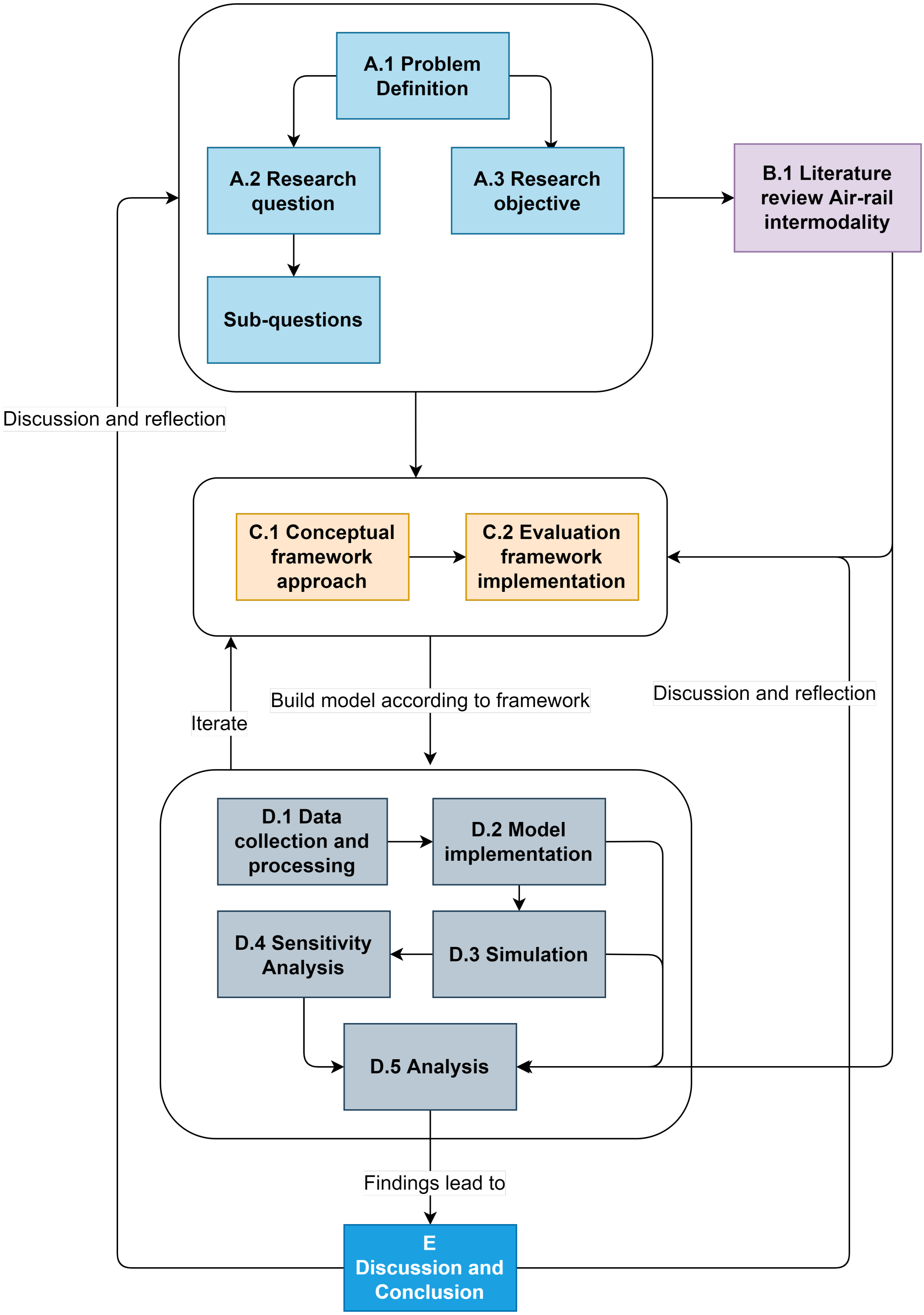


Figure 2.1: Research framework.

3

Literature Review of air-rail intermodality

In this literature review, a review is conducted of literature related to the research question and sub-questions posed in chapter 2.

This review is done in three main focus points, with subtopics in each categorized by research purpose. Each subtopic receives an introduction giving its relatability to the research question(s), a review of the literature and a short conclusion.

In section 3.1, a review of the background to the problem, focussing on future passenger and air traffic growth forecasts, and the effects of airport congestion is conducted.

In section 3.2, the question of how intermodality can play a role together with air travel to solve some of these challenges is researched. The competitiveness of both travel modes from a passenger perspective in terms of door-to-door travel time, and how ground transportation cooperates with air travel is examined. Studies on replacing air travel by rail, and the potential environmental and operational benefits of intermodally integrating airlines, airports, and railway operators are investigated.

Finally, in section 3.3, the environmental effects of the use of air transportation and ground transportation are considered. Carbon dioxide emissions during operation, but also a peek into the lifecycle emissions which is often left out of similar literature is studied.

3.1. The relation between air travel growth and congestion

Two sub-questions from the main question that will be partly researched here are: "How can air-rail intermodal transportation contribute to the high-level European mobility and sustainability goals?" and "What are the possible environmental and operational efficiency gains by integrating air and rail in Europe for airlines, airports, and rail operators?". It is necessary to understand what the future holds to get a bigger long-term picture for the research question's validity.

Some background to the European mobility and sustainability goals considered is given first. The European Green Deal calls for a 90% reduction in greenhouse gas emissions from transport (European Commission 2022a). The European Commission saw that the airport capacity "needs to be optimized and, where necessary, increased to face a growing demand for travel to and from third countries and areas of Europe otherwise poorly connected, which could result in a more than doubling of EU air transport activities by 2050. In other cases, (high speed) rail should absorb much medium distance traffic" (European Commission 2011b). Last but not least, the Flightpath 2050 aims to enable 90% of citizens to reach any place in Europe within 4 hours door to door by 2050, for journeys including an air segment (European Commission 2011a). Very challenging goals indeed, require out-of-the-box thinking and a multifaceted solution. The European Commission has in mind already that high-speed rail (HSR) can absorb medium-distance traffic, which is supported by the number of subsidies given to create HSR all around Europe.

3.1.1. Future air travel growth

The number of passengers is estimated to increase from 4.5 billion in 2019 to more than 12 billion passengers worldwide by 2050 considering the estimated loss of 2-3 years of growth due to COVID (IATA 2022b; IATA 2021). This passenger growth of almost 167%, means more flight movements to carry the passengers. A 44% increase in flights is expected in Europe alone for the year 2050 compared to 2019 in the base traffic scenario performed by EUROCONTROL (2022a), which leads to increased congestion and aviation emissions. The capacity constraint effect on the number of flights can be seen in Figure 3.1, and the estimated aviation carbon emissions can be seen in Figure 3.2. It is estimated in the base scenario of traffic in 2050 that 3% of flight demand cannot be filled. This is including an input assumption that 56 city pairs are implemented with HSR. It is unsure whether this study by Eurocontrol included the effects of future seat sizes, a past study stated

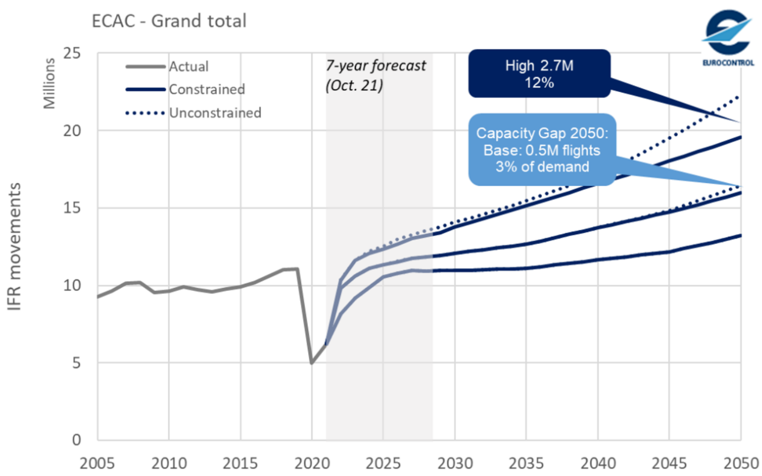


Figure 3.1: Eurocontrol flights forecast for 2050, edited for clarity (EUROCONTROL 2022a).

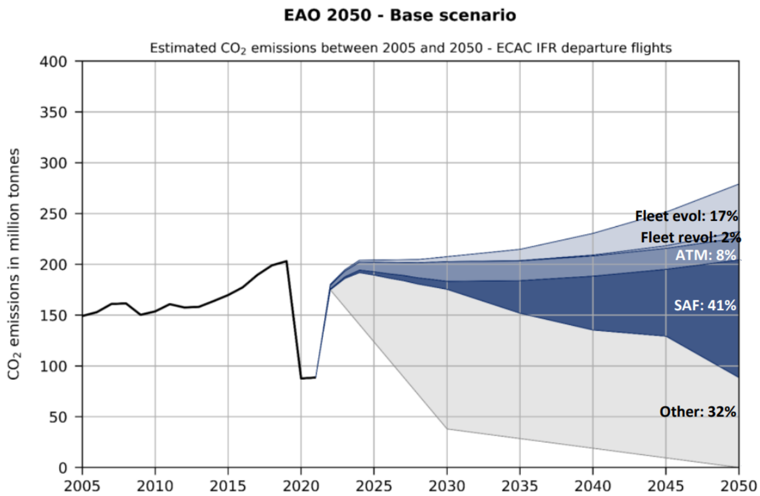


Figure 3.2: Eurocontrol carbon dioxide emissions forecast for 2050, edited for clarity (EUROCONTROL 2022a).

"...continuous increase in average aircraft size over recent years in Europe. In the future, we expect the trend to continue, with a progressive increase in the use of widebodies between 2025 and 2040 for the medium- and long-hauls" (EUROCONTROL 2019). In the past study, a capacity gap of 8% of the demand was predicted (1.5 million flights). Interestingly, if the electric and hydrogen aircraft that are needed to decarbonize aviation are introduced, this would push the average aircraft seat size to decrease. Hence, the capacity constraint could be even larger, given other modes of air travel are on the rise as well, such as urban air mobility. The capacity constraints issue is covered to a greater extent in the next subsection, subsection 3.1.2.

In the past 40 years, air transportation's most growth has been on city-pairs with a major hub city (IATA 2022b). In Figure 3.3, the growth of secondary cities is nothing compared to the growth at hubs. So, hubs will be increasingly congested. Many passengers travel in the short-haul market as can be seen in the distribution of passengers per kilometer given in Figure 3.4 (Ghosh and Terekhov 2015).

In conclusion, future air travel growth will make the challenge of greening aviation and fast reliable mobility in Europe much more difficult. It is clear that a large number of passengers travel short distances. Hence, a large number of multi-stop passengers could use intermodal transportation, if the connecting flight can be reached on-time. Also, direct passengers flying short distances are also a big market for HSR. However, this is considered out of the scope of this study and will be done in future research.

3.1.2. Delay and capacity constraints

A major cause of flight delays is inadequate capacity in the air transportation system. The challenge facing the aviation industry from air traffic demand growth is congestion in many airports, especially hub airports (Flores-Fillol 2010). Congestion causes flight delays, cancellations, and missed connections that affect passengers and airlines' bottom line. The study by Flores-Fillol (2010) found that airport congestion depends on the

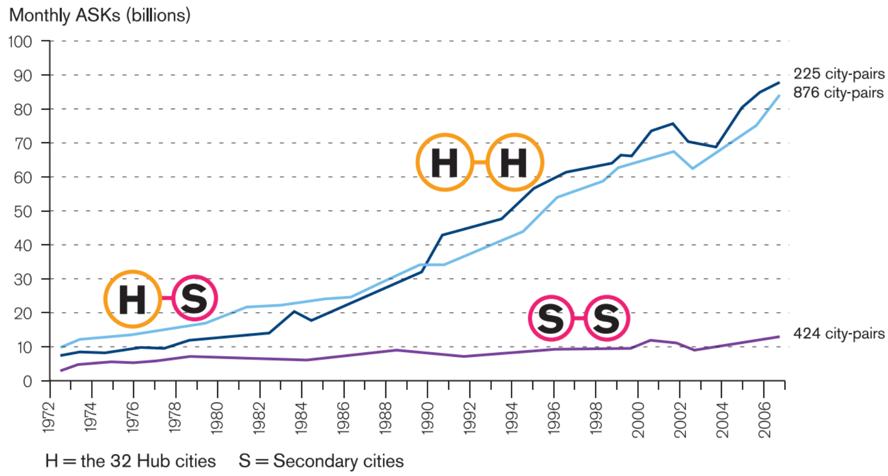


Figure 3.3: The growth of airports categorized by hub cities and secondary cities from the 70s to the 2000s, network growth is concentrated at large hub cities (IATA 2022b).

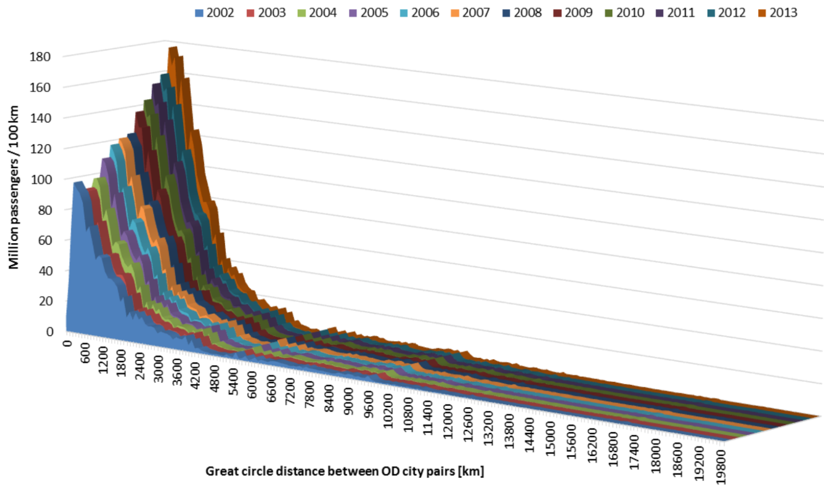


Figure 3.4: Passenger demand distribution from 2002 until 2013 trend in million passengers and 100 km intervals of great circle distance (Ghosh and Terekhov 2015).

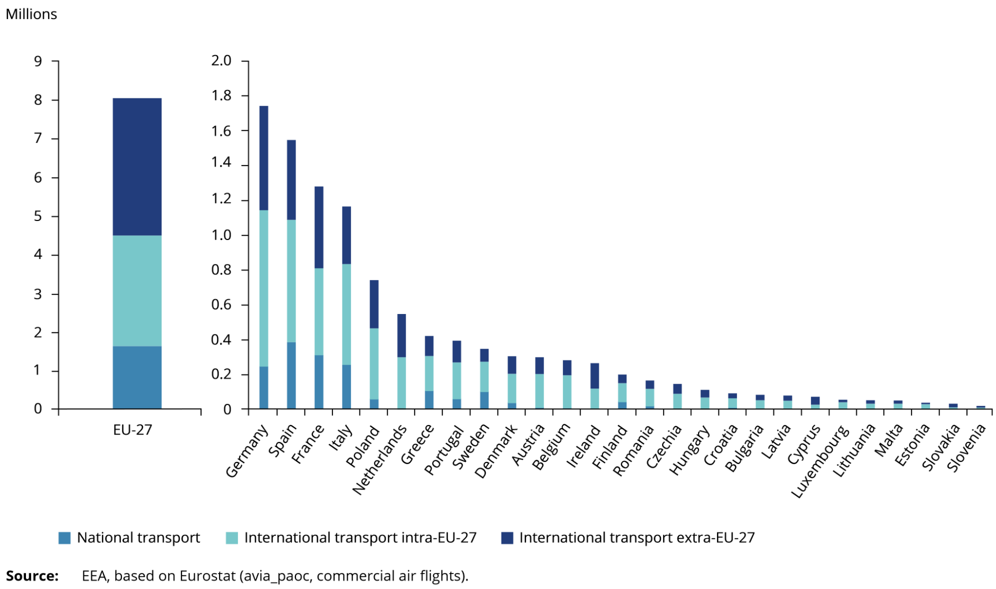


Figure 3.5: Number of flights by transport type per EU 27 country in 2019 (European Environment Agency. 2021).

number of aircraft operations, and by using overly small aircraft airlines schedule many flights aggravating congestion at hubs. It concludes rightly that larger networks may exaggerate the inefficiency associated with congestion.

Lubig et al. (2021) found that hub airports operating at capacity limits have downstream effects on the hub airlines' operation performance. A simulation illustrates this effect, increasing capacity by 10% at London Heathrow improves the rate of successful flight connections from British Airways by 10% and decreases the in and outbound delay at London Heathrow by 42% and 80%. Current hubs are already facing capacity constraints due to congestion (Marc C. Gelhausen, Berster, and Wilken 2013). Marc Christopher Gelhausen et al. (2022) expect that almost 50 million and more than 250 million passengers will not be accommodated in 2030 and 2040 worldwide, respectively. This is despite mitigation measures such as increasing airport capacity and utilization as well as increasing larger aircraft over time to carry more passengers per flight.

Hub airports are a necessity for mobility. Especially in cities geographically located on the periphery of Europe, where a transfer at one of the major hub airports is needed (Jaksche and Asmer 2021). (Zou and Hansen 2012) finds that capacity constraint suppresses demand and reduces flight frequency. (Luttmann 2019) stated that from a passenger perspective the layovers present in hub-and-spoke networks are detrimental as it adds to the total travel time. According to the study narrowing this gap between the connecting flights is a trade-off for the airline, however, as it has the adverse effect of increasing airport congestion. There are many practical capacity mitigation methods airports set to limit average delay (De Neufville et al. 2013; Knabe and Schultz 2016; Hu et al. 2022). These studies give some examples aside from adding new runways which require large investment: re-organisation of traffic operations into off-peak times, diverting traffic to less congested airports, and using larger aircraft are some of the options to react to congestion. "Many airline executives and aviation officials believe that the principal threat to the long-term future of the global air transportation system is the apparent inability of available runway capacity to keep up with growing air traffic demand at many of the world's most important airports" (De Neufville et al. 2013, see page 323).

Source	**Key Findings**	**Conclusions**	**Relation to this study**
Flores-Fillol (2010)	Airlines schedule many small aircraft flights which exacerbate congestion. Larger networks increase congestion inefficiency. Alliances lead carriers to include partner's congestion.	Congestion pricing could help alleviate the problem, so carriers use larger aircraft and reduce flight frequency.	A solution that reduces small aircraft while maintaining connectivity to reduce congestion is needed.
Lubig et al. (2021)	10% capacity increase at EGLL leads to -42% inbound delay, -80% outbound delay, -33% additional taxi-out time and -56% queue time at the runway from arrival flights.	Increasing capacity at the hub airport leads to improved direct flights to the hub and flight connection success for mainstream airlines who use the hub airport as a hub and not as a spoke.	Reducing the number of flights is equivalent to increasing capacity, by reducing feeder flights the capacity increases and hence less delay is caused.
Marc C. Gelhausen, Berster, and Wilken (2013)	6%-15% of global air traffic is being operated in capacity-constrained conditions.	The number of constrained airports will grow rapidly, and the means of enhancing capacity will probably not suffice to keep pace with the growth in demand.	Capacity issues are expected to get worse, which strengthens the need for solutions.
Zou and Hansen (2012)	Capacity constraints suppress demand and reduce flight frequency. With higher capacity, airlines raise frequency while decreasing aircraft size.	Facing delays, airlines lower frequency and pass delay cost to passengers. The benefit of increasing capacity diminishes as the imbalance between capacity and demand is mitigated.	It gives an understanding of airline actions on capacity. It is clear that as airports become more capacity constrained, the flight frequencies will reduce leading to more transfer time.
Luttmann (2019)	Inverse relation between fare and layover time. Cheaper multi-stop flight when layover time increases.	Airline is able to reduce layover time by narrowing the gap between flights, however, this increases airport congestion.	Layover times are detrimental to the total travel time for passengers, which leads to a cost decrease.
Hu et al. (2022)	Significant differences between airports' congestion status, over 85% of airports in china are not overloaded. Ten airports in China are extremely capacity-constrained and they serve as international or regional hubs.	Airport location, orientation, and linkage to the local economy are closely related to airport capacity constraints. Most airports will have sufficient capacity reserves in the future (except for some international airports).	Hub airports, exactly the ones needed for global connection are experiencing capacity issues. This study should find a way to solve this capacity problem.

Table 3.1: Summary of delay and congestion.

In conclusion, it is clear that congestion is a growing concern which makes the Flightpath 2050 goal harder to reach. This is also one of the considerations in Waypoint 2050 (Air Transport Action Group 2022). The capacity limits will help keep the average delay at a reasonable level, but will not enable connectivity growth. As congestion increases, larger aircraft with lower frequencies might be used, which increases transfer time.

This means that over time using intermodal transport becomes more competitive in terms of travel time. Of course, this air travel growth leads to more aviation emissions.

By decreasing the number of short-haul flights using intermodality, the delay of the remaining flights decreases, and the ability of airlines to have less connecting time increases (by increasing the frequency of the remaining routes). Hence, the passengers will have a shorter door-to-door travel time. Also, by decreasing delay, as mentioned by Lubig et al. (2021), fewer flights are slowed in the air or waiting to take-off due to queues. Hence, leading to fewer emissions. Of course, the flights that are replaced by rail will also decrease the total emissions of aviation, shifting it to lower-rate transportation emitters. But, the freed slots might lead to longer-haul flights being implemented which increases emissions. This repurposing of freed slots effect is studied in subsection 3.2.1 and subsection 3.2.2.

3.2. Intermodal effects and feasibility

In the previous section, the growing problems facing aviation and mobility, in general, were researched. Firstly capacity, the growth in air traffic will lead to the demand not being able to be met. Secondly, the carbon dioxide emissions released due to air traffic particularly. Thirdly, the travel time goals from the European Commission stem from the need for people to travel to their destination as quickly as possible. To what extent is rail transportation a better alternative in terms of travel time, and what are the possible environmental and operational gains of intermodal integration? These are some of the sub-questions given in chapter 2, which are explored in the following subsections.

3.2.1. Competition effects rail integration with air

Competition here is limited to the effects on flight frequency and demand. Papers solely on fares, revenue sharing, and intermodal agreements are out of the scope of this study.

Y. Wang et al. (2020) introduces low-cost HSR (LCR) to a full-service HSR (FSR) and air transport and proves analytically that the LCR would reduce FSR and air traffic by about 33% for the Paris to Marseille route (around 700 km). Yuan et al. (2021) studied various papers on the emergence of HSR on air travel. They found that the emergence of HSR in China had a substantial negative effect on the flight frequency of short-haul and medium-haul flights (Wan et al. 2016), and air travel demand decreased (Q. Zhang, Yang, and Q. Wang 2017). But, the impact on flight service levels decreases as the travel time of HSR increases (Dobruszkes, Dehon, and Givoni 2014).

C. Wang, Jiang, and A. Zhang (2021) flips the script and studies what an HSR operator does to respond to the entry of an airline. The study found that airline entry reduces the frequency of HSR service, more so if the HSR has only a small number of stops. Regarding train size (measured by the number of passengers carried), the HSR with many stops reduces its train size but the HSR service with a small number of stops does not significantly change its train size.

In a study by Milan (1993), it was stated how HSR can compete with air traffic due to a better frequency with larger capacity, a high level of regularity (traffic with minimal delays), high reliability (insensibility to the negative influences of weather, and physical accessibility as the railway stations are more favorably located. The study made a numerical example to show that HSR can compete with air travel over large distances (200-1200 nmi).

Many studies found that HSR entry causes a decrease in air traffic, however, for long-haul markets (over 1000 km) an increase in air traffic is induced after HSR entry if HSR travel time is over 5 hours longer than air travel time (Gu and Wan 2020). The study found under these conditions that airfare decreased, hence leading to an increase in air traffic.

Source	Key Findings	Conclusions	Relation to this study
Y. Wang et al. (2020)	LCR introduction leads to reduced FCR traffic and reduced air traffic. Paris- Marseille route had 33% less air traffic, 14% less full cost HSR traffic, and 37% increase in total rail traffic.	LCR attracts new passengers, but most would have traveled by air or FCR. LCR especially is a large threat to low-cost air.	Analytical proof that the introduction of LCR reduces air traffic and increases the frequency.
Wan et al. (2016)	HSR entries per country differ but lead to a significant drop in airlines' seat capacity in the short-haul (<500 km) and medium-haul (500 km-800 km) air markets using datasets of Japan and China from 1994-2012.	China compared to Japan has been experiencing prolonged delays, because of air traffic congestion, perhaps making HSR more attractive.	Empirical investigation that HSR entry changes air seat capacity.
Q. Zhang, Yang, and Q. Wang (2017)	Quarterly air passenger demand data from 2010 to 2013 analyzes the effect of HSR on China's big three airlines, and a strong negative impact on air transport demand occurs.	While HSR impact is strong in thin markets it is insignificant in thick markets. Passengers choose HSR more on travel time than HSR service frequency.	Again confirmation of reduction of air travel due to HSR entry. Interesting that travel time is more important than the frequency for HSR.
Dobruszkes, Dehon, and Givoni (2014)	Ex-post analysis considering 161 routes EU-wide shows shorter HSR travel times involve fewer airline seats and flights with similar impact. The impact of HSR frequency was much more limited.	More air travel if HSR travel time is longer, however, the effect decreases for less than 2 hours extra HSR travel time. Hubbing strategies involve more air services, rail as feeder proposed. However, freed slots may be reused.	Again in Europe, fewer aircraft seats are filled as HSR enters the market. 2 hours extra travel time HSR acceptable. Future studies should consider the freed slots effect from modal substitution.
C. Wang, Jiang, and A. Zhang (2021)	The entry of an airline has a negative impact on HSR with a small number of stops and reduces HSR train size with a large number of stops.	Entry may reduce social welfare as small regional markets are hurt, decreased operational efficiency of HSR (improves service frequency with reduced train size but more per passenger environmental footprint).	Understanding the opposite effect when an airline enters an established HSR market. It seems the policy should limit these entries.
Milan (1993)	Analysis model to determine conditions for the competition of HSR and air transport (AT), competing on the cost which is made from travel time and fare. Examples show that HSR can compete with AT over a large range (370 km - 2200 km)	Model can be used by both HSR and AT operators. Can be used to gain an understanding of planners, and passenger choice behavior.	The model created has used an example of 20 cities in the European Community and found competition is possible up to 2200 km.
Gu and Wan (2020)	Catchment expansion may explain post-HSR entry air traffic increase. Air traffic increases after entry of HSR if rail travel time is over 5 hours longer.	HSR catchment expansion is strongest for feeding distances below 1.5 hours. HSR may induce more air traffic and emissions from the airlines in medium-haul and long-haul markets, due to decreased airfare.	Clearly, if the HSR feeds into hubs and also is competitive in price, airlines will decrease their prices and hence consumers will buy more if they also save on time versus the HSR.

Table 3.2: Summary of competition effects rail integration with air.

In conclusion, it seems that analytical and empirical models have proved that in general HSR entry reduces air traffic. Some ranges of significant competition are found. There are some interesting drawbacks to reducing air traffic for short-haul routes as these could be used for longer-distance routes. This will be discussed, in subsection 3.2.2.

So looking back at the questions posed, it seems that HSR reduces congestion by means of the reduction of flights (capacity solution). This of course also leads to a reduction in emissions (environmental solution). Also, the travel time of HSR is competitive to introduce a modal shift, hence passengers see a benefit in travel time in some cases (time benefit).

3.2.2. Aviation cooperation with rail

Some benefits of cooperation between HSR and air travel are discussed here, but also some drawbacks. Disruption and congestion relief, increased catchment area, increase reliability, and door-to-door mobility are all supposed benefits. There is a case to be made that the freed-up short-haul flight slots will be used for long-haul flights being used which will also be discussed.

Sato and Chen (2018) analyzed cooperation between the airline and HSR sectors. It found that improving accessibility from airports to rail networks between the hub and the final destination led to a decrease in market share for connecting flights. They found that for airport operators, one possible benefit is that if the freed slots or legs due to HSR and airline integration are used for long-haul flights, the airport can obtain additional landing fees and possibly increase the number of passengers. But, this comes to an increase in global environmental impacts for aviation if these long-haul flights represent additional ones. Xia and A. Zhang (2017) found that consumers always benefit from less air-rail connecting time, operators won't have an incentive to integrate unless the cost to integrate is low enough. The study noted that reducing air-rail connecting time when the hub airport is constrained in capacity enhances total surplus.

van Goeverden (2009) found evidence that time, cost, and number of interchanges are the quality variables for both long-distance train and car use by tourist travelers in Europe. The study continues by stating that the probability of train use is highest between "600 and 900 km and lowest between 1400 and 1500km". It is also unlikely for train use to occur between 100 and 200km according to the study. Note that this is smaller than the distances of city pairs in the Netherlands, so NS would not like to hear this...

Jiang and A. Zhang (2014) analyzed the consequences of cooperation between a hub-and-spoke airline and an HSR operator when the hub airport can be capacity-constrained. The study found that cooperation reduces traffic in markets where prior modal competition occurs: "When air and HSR services are close substitutes, the cooperation will significantly reduce the airline's output in the HSR-accessible market, freeing up a large amount of hub capacity, which can be used in the HSR-inaccessible market" (Jiang and A. Zhang 2014).

Givoni and Banister (2007) states that due to congestion and environmental problems faced by the air transport industry, railways can have a greater role in working with airlines to provide transport service for distances up to 800km. They argued that because many air journeys involve two flights, the air journeys can be replaced by a rail journey and a flight. In this way, they reason that the gradual extension of HSR networks can provide a feeding service to long-haul flights at hub airports and make better use of air capacity. So, HSR can complement the airline industry, especially for hub-spoke networks.

A study focused on door-to-door travel in 2035, Kluge, Ringbeck, and Spinler (2020) performed a two-round Delphi survey with 38 experts. It stated that intermodal, door-to-door travel is gaining momentum for airlines, airports, and feeder traffic providers.

Takebayashi (2016) used numerical simulation to show that cooperation between HSR and smaller airports can reduce congestion at larger airports. Li et al. (2022) modeled the effect of airline and HSR cooperation on multi-airport systems and found that airlines are more likely to provide air-rail intermodal integration in the presence of costly hub airport congestion. This is true only if there exists a low degree of substitution or when the competition on the direct air route is not significant the study found.

Laplace, Marzuoli, and Feron (2014) saw the use case of using air rail multimodal transportation to improve passenger experience during irregular operations (snow, crisis events, etc.). It states that the airport multimodality, which is the linkage between the airside and landside is essential to deal with irregular operations. Both airport access and network integration are crucial for efficient disruption relief which comes at a high infrastructure cost among others.

A study done by Vespermann and Wald (2011) collected the aims airports have with supporting intermodality at their airport from various studies:

- To expand the catchment area (Givoni and Banister 2006).
- Airports who want to shift air traffic to the ground infrastructure system in order to increase airside capacity at the airport (Everett 2002). Intermodality allows for airside volume growth while sticking to the existing airport and terminal limitations according to Vespermann and Wald (2011).
- Meeting customer needs for seamless transportation: less congestion and more reliability (Vespermann and Wald 2011).

Airlines aside from the better connectivity may also try to achieve "capacity releases by substituting short-haul flights by alternative short-distance feeders like high speed trains" (Vespermann and Wald 2011). This leads to benefits for rail operators as they can then increase their own load factors, especially during off-peak hours. Vespermann and Wald (2011) states that airlines especially at major airports where slots are rare and extremely expensive can use intermodality to substitute their short-haul flight slots (the available time window for arrival or departure) for more profitable long-haul routes by increasing frequency or increasing connectivity.

Source	Key Findings	Conclusions	Relation to this study
Jiang and A. Zhang (2014)	Airline-HSR cooperation reduce air traffic in HSR accessible market, freeing hub capacity which then increases traffic in the connecting market and HSR-inaccessible market.	Economies of traffic density alone cannot justify airline-HSR cooperation. When substitutability is high then “Such cooperation improves (reduces) welfare if the hub airport is (is not) seriously capacity-constrained.”	Freed-up slots lead to more flights in HSR-inaccessible markets which in general mean longer flights.
Givoni and Banister (2007)	Railways can be more than the provision of access to airports, cooperation can lead to integrated services for journeys up to 800km.	Integration of air journeys by rail journey and a flight with a transfer at the hub airport could provide a better use of available air capacity.	The discussion given in the study offers many insights for this research as it is the paper that really discussed the idea of integrating rail into multi-stop flights.
Takebayashi (2016)	Numerical computations show that collaboration between HSR and a smaller demand airport in terms of injection strategy reduces congestion of bigger airports.	Collaboration improves social welfare. Airlines prefer collaboration between HSR and hubs, but it is undesirable for passengers as it invites congestion and leads to decreased international traffic.	Study has some issues with its methodology which makes it somewhat irrealistic, but could be that feeding non-hub airports for international flights are a viable strategy.
Li et al. (2022)	Effects of air and HSR cooperation on multi-airport systems reveals airline is more likely to become intermodal in presence of costly hub airport congestion and low degree of substitution.	Promising improvements to multi-airport systems and increased welfare benefits. Important to maintain inter-airport competition when air-HSR service is introduced.	What happens to ORY if CDG only has air-rail intermodality? Gives factors for airlines integrating with HSR.
Laplace, Marzuoli, and Feron (2014)	Case study for passenger-centric approach using multimodality and CDM principles to minimize the impact of severe disruptions.	Extending A-CDM has real and significant benefits for passengers, i.e., by: CDM processing at the network level, shifting focus to the passengers, accurate reflection of flight delays, etc.	Operational benefit of intermodality.
Vespermann and Wald (2011)	Survey findings indicate high modal concentration and dependence on individual access modes, while airport managers intend to reduce these modal shares and increase high-occupancy airport access modes.	Case study shows air-rail intermodality to be successful and efficient in offering connection to a comprehensive network and frequent access services. Possibility to reduce short-haul markets by providing lower travel time. No ’one-best-solution’ for all airports.	Airport stakeholder understanding for integration success.

Table 3.3: Summary of aviation cooperation with rail.

In conclusion, cooperation with rail brings forth many benefits, but there are still many question marks as these cooperations while increasing in real life are yet quite young. This preliminary research will prove at least that it is indeed possible to combine air and rail journeys while maintaining a similar total travel time. It is interesting that this approach has not been explored since being reasoned in 2007 by Givoni and Banister (2007), perhaps the data was not readily available or HSR networks were not as extended as they are currently.

In the author’s opinion, having freed-up slots for long-distance flights is great for connectivity and social-economic welfare. Future generations should be able to travel all over the world. As technology increases, revolutionary aircraft will reduce climate emissions. The capacity problem has to be solved for this because as of now revolutionary aircraft tend to have smaller seat sizes which leads to the need for more aircraft for a single route. Reducing congestion caused by smaller aircraft of high frequency on routes that might as well be served by HSR due to short distances seems to be a great solution for this problem. Cooperation rather than competition is key here. Of course, the freed-up capacity can just be withdrawn to reduce the unwanted environmental impacts if policymakers so desire (Givoni and Banister 2007).

The current problem is that there is a duplication of air capacity and rail capacity. Heathrow and CDG still have high-frequency flights despite HSR operating since the 90s. This is probably because of the feeder flights that are needed to provide the long-haul more profitable routes according to Givoni and Banister (2007). Hence this study will try to reduce feeder flights, by replacing them with “feeder rail”.

3.2.3. Air substitutability by rail

Studies with a focus on replacing flights with rail are presented. A focus on studies with findings related to travel time, CO2 reduction, or flight reduction is made. The capacity of the rail network to handle additional passengers is also included if possible. This aims to explore the fundamental part of the main research question. To see the scope of literature that has studied the main research question and their conclusions.

In Avogadro et al. (2021), route substitutability based on increased travel time and cost for intra-European (single leg) flights found 3% of seats can be canceled without a significant increase in travel time. Note, that

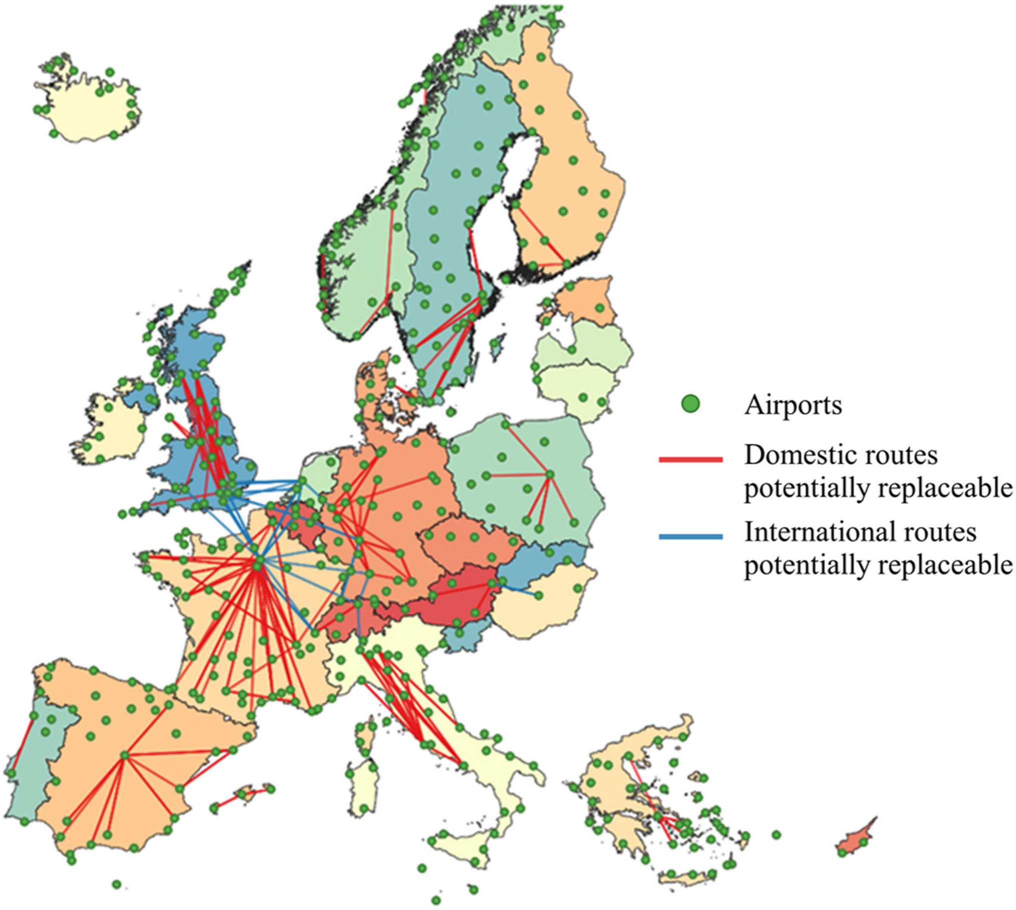


Figure 3.6: Domestic and international routes potentially replaceable depending on 20% weighted increase in travel time (Avogadro et al. 2021).

no train emissions were accounted in the study. The potentially replaceable routes are given in Figure 3.6. A similar method of comparing specific city pairs was used by Baumeister and Leung (2021) but in this case for Finland which has no HSR at the time of writing. The main findings of this study in Finland were that the rail is competitive in terms of travel time and emissions reduction.

Montlaur, Delgado, and Trapote-Barreira (2021) created an analytical model to estimate gate-to-gate CO2 emissions and travel time to identify European routes where rail would be a viable alternative both from the emissions and total travel time perspectives. This study matches the goal of this research, albeit the time constraint and multi-stop flights aspect are missing. Also, this research aims to provide routes for all of Europe, which requires a more data-driven approach.

Rothfeld et al. (2019) evaluated 22 European airports' access and egress times. The analyses showed great variations in airport access and egress speeds between European airports and even greater discrepancies between road and transit times. This means that replacing intra-European multi-stop flights has an advantage as the airport access and egress times would be eliminated.

According to EUROCONTROL (2021) that HSR can replace air below 500km which represents 24.1% of European flights, which accounts to 3.8% of aviation emissions. The think paper continues by stating that in the 500-1500km sector (46% of flights and 22% of CO2) HSR has much less ability to substitute successfully for air. The think paper finalizes by stating that multimodal solutions that combine air and rail are highly attractive in terms of optimizing sustainability and improving connectivity.

Source	Key Findings	Conclusions	Relation to this study
Avogadro et al. (2021)	Intra-European short-medium-haul air routes substitutability analyzed by higher travel time and generalized cost induced by modal shift shows domestic routes are mainly replaced. Potential CO2 savings and replaceable offered seats are not equally distributed.	26 million seats (3% intra-European) may be canceled without any significant increase in travel time, with Air France leading the bunch. This policy would only affect areas already efficiently served by ground transportation.	More top-down data-driven method for single-leg flights includes cost which this study does not. Uses a weighted increase in travel time which is interesting to include in this study.
Baumeister and Leung (2021)	Short-haul flights are easily replaceable even by conventional rail. Non-HSR can compete with air travel times up to 400km in Finland.	Substituting short-haul flights with non-HSR in Finland can reduce emissions by 95%	Similar to previous, single flights. Looks a bit deeper into the capacity of trains, and door-to-door travel time and emissions.
Montlaur, Delgado, and Trapote-Barreira (2021)	Analytical models to calculate gate-to-gate CO2 emissions and travel time based on flight distance and on number of available seats.	The model CO2 results are similar to other calculators. Applied to different EU routes show gCO2 per available seat kilometer is always much lower for rail than for air, especially below 800 km, with travel time equivalent for air and rail up to 600 km.	Great real-life example of the benefits of rail vs air at short distances. Still top-down with time scheduling approximations, a more precise data-driven approach is needed which will be given in this study.
EUROCONTROL (2021)	HSR potential to replace air below 500 km, responsible for 24.1% of flights, 3.8% of emissions. Studies proposing air-rail shifts underestimate the significant economic and environmental impacts of the expansion of HSR lines. Multimodality is highly attractive to optimize sustainability and improve connectivity.	Clear advantages of rail over the air in terms of emissions. The solution is “plane and train” instead of “plane vs train”	The socioeconomic and biodiversity constraints of HSR have to be studied, existing rail has a lot of potential to cooperate with air to replace short distances (500 km), and probably more in case of multi-stop flights.

Table 3.4: Summary of aviation substitutability with rail.

The author finds the 25% decrease of flights below 500km found by (EUROCONTROL 2021) might make a lot of queues at Amsterdam Schiphol Airport quite a bit shorter and also helpful in making aviation more sustainable. While the 500-1000km could be better achieved by replacing multi-stop flights. The author finds that a data-driven method can lead to a better answer than a fixed distance-based rule. Clearly, if each country does the case study per airport pairs as was done by Baumeister and Leung (2021) and identifies routes that are replaceable by train in less time and promote this and subsidizes these routes, passengers would choose the better option. Avogadro et al. (2021) argues that a focus on areas only efficiently served by alternate travel modes should be placed. A research gap exists for the main research question for a bottom-up data-driven analysis of the air and rail European transport system for multi-stop flights, considering both travel time and carbon dioxide emissions. Very active research field in air vs rail, with plenty of benefits for society and a hot topic in Europe.

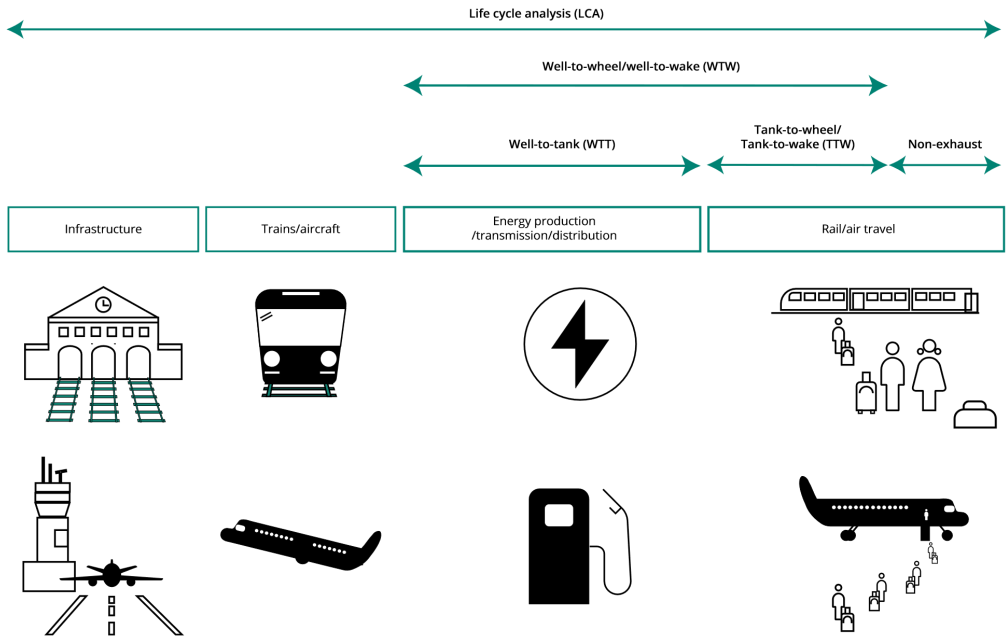
3.3. Sustainability of air travel and ground transportation

The main question seeks to find the carbon emissions difference between rail and aviation. This section focuses on the life cycle and operational carbon dioxide emissions for the various transport modes. Noise and habitat destruction for example are significant issues for rail. Non-CO2 also has large effects on global climate (Turgut and Usanmaz 2017). Non-CO2 emissions are accountable for around three times the rate associated with air travel’s CO2 emissions according to (Lee et al. 2021). However, to be able to compare air versus rail/ground transportation GHG emissions, CO2 is an apples-to-apples comparison. Hence, non-CO2 environmental effects are purposefully avoided.

3.3.1. Life cycle assessments of air and rail transportation

Life-cycle perspectives of the emissions of transport modes typically considered according to (Noussan, Campisi, and Jarre 2022) are:

- Direct emissions (also known as tank-to-wheel (TTW)) are emitted directly by the vehicle during its use related to fuel consumption. Typically, CO2 emissions factors are estimated based on distance in addition to several parameters including vehicle type, fuel, size, load factor, etc.
- Indirect emissions (also known as well-to-tank(WTT)) are related to the fuel supply chain from extraction to storage.
- Manufacturing emissions caused by the production of the vehicle.



Source: EEA compilation.

Figure 3.7: Compilation of emission categories (European Environment Agency. 2021).

- Infrastructure: from the construction and maintenance of transport infrastructure. For example, the asphalt of a highway, or the steel of the rail. Especially for HSR this is often not overlooked as it is not shared with other transport modes.
- Services
- End-of-life emissions from the possible recycling or reuse of components.

The European Environmental Agency compiled these emission categories in a helpful diagram, given in Figure 3.7.

Life cycle assessments (LCA) contain all the mentioned perspectives. The combination of TTW and WTT is called well-to-wheel (WTW) emissions. (Noussan, Campisi, and Jarre 2022) accumulated over one thousand emission factors and the results are given in Figure 3.8.

A whole system approach is taken in (Federici, Ulgiati, and Basosi 2009), with the aim to reveal the hidden environmental costs of rail, road, and air. In the study, it is argued that the comparison between operational emissions is unfair due to the resource demand and an environmental load of infrastructure construction. From the study, it is also clear that different evaluation methods do not converge: using material flow analysis (MFA) and emergy synthesis (ES) shows that airplanes are always competitive with HSR and intercity trains, whereas the Embodied Energy Analysis (EEA) indicator shows that rail is competitive until a distance of 1300 km. This study gives a great example of the material and environmental damage caused by high-speed rail travel.

Westin and Kågeson (2012) found that in order for high-speed rail to offset its embedded emissions, high-emitting traveling modes such as air travel must shift to rail.

Kortazar, Bueno, and Hoyos (2021) considered the construction and maintenance phases of the HSR lines of Spain in 2016 together with their operation that year and verified that the construction was justified in terms of reducing environmental impacts and energy consumption.

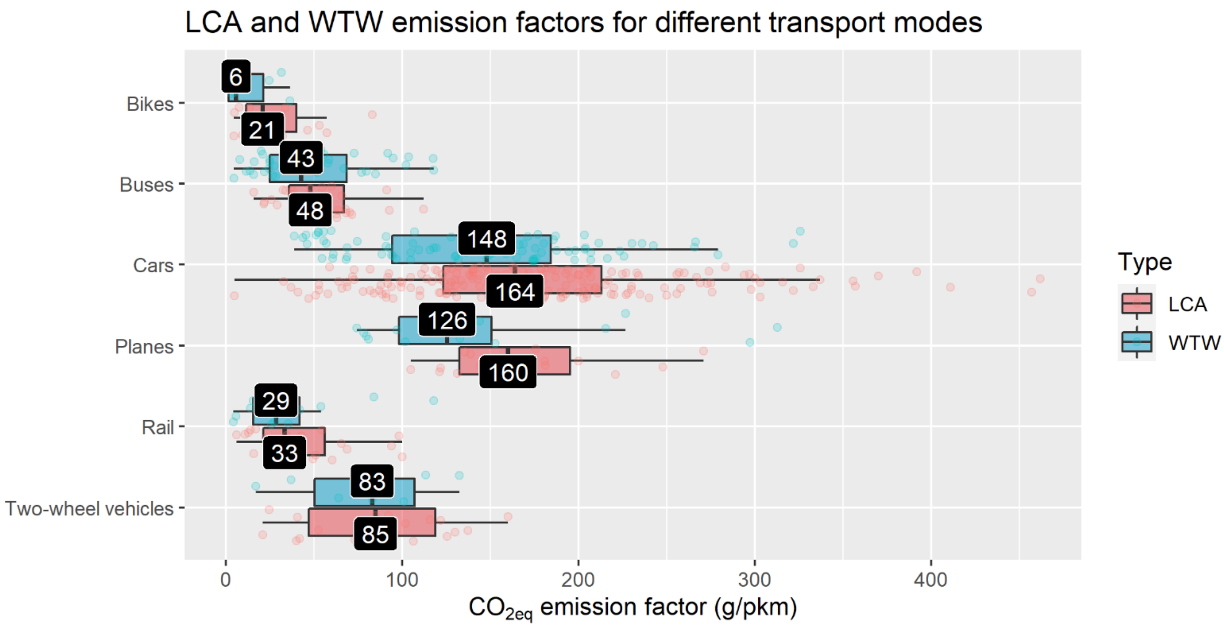


Figure 3.8: Emissions factors by transportation mode (Noussan, Campisi, and Jarre 2022).

Source	Key Findings	Conclusions	Relation to this study
Noussan, Campisi, and Jarre (2022)	Comprehensive overview of research comparing emissions factors and discussing main drivers and parameters that affect variability.	Useful results for researchers and policymakers, showing clear differences between different transport modes.	Helps with selecting emission factors for various ground transportation modes.
Federici, Ulgiati, and Basosi (2009)	Evaluation methods do not converge: using MFA and ES indicators shows that air is always competitive with HSR, whereas the EEA indicator shows that rail is competitive until a distance of 1300 km.	When cars and trains are misused (below 50% load factor, or range of distance where other modes are better, etc.) even air can be the “less resource-intensive” option.	Big picture emissions view of the hidden (huge) biophysical and environmental costs usually unspoken of.
Westin and Kågeson (2012)	Monte Carlo simulation to analyze the benefit of new HSR, finds it depends on CO2 from energy generation and degree of modal substitution from air. Not many tunnels should be used.	To make new HSR worthwhile, high traffic volumes of annual one-way trips are needed, and the traffic must come from aviation.	For HSR embedded emissions to be offset, aviation seats must become the HSR seats, and it is site-specific. This research can make a step toward creating that volume.
Kortazar, Bueno, and Hoyos (2021)	LCA of Spanish HSR lines in operation in 2016. HSR was justified for some corridors in terms of environmental impact reduction.	Alternatives to HSR (increasing road load factor, electric vehicle usage) provide better environmental balance as train volume is not expected to increase considerably.	The need to increase HSR volume for its viability.

Table 3.5: Summary of life cycle assessments air and rail.

In conclusion, the research is conflicting. More research has to be conducted with respect to the embodied emissions of rail and other forms of ground transportation as was suggested in Federici, Ulgiati, and Basosi (2009). The environmental benefits of introducing HSR have to be studied on a case-by-case basis depending on expected demand. This research does not only consider HSR as the alternative but the entire ground transportation transit network. Given the number of infrastructure projects in Europe being pursued, one hopes that these lines will be utilized maximally European Commission 2022b. This research aims to give a framework using real data to show the journeys which would have been equal in terms of travel time, with the aim that passengers shift to rail for these journeys and hopefully fill current and future completed infrastructure projects.

3.3.2. Direct emissions of different travel modes

B. Wang, O’Sullivan, and Schäfer (2019) show that investments in HSR can effectively contribute to reducing emissions from domestic aviation, and this effect increases if the electricity generation sector is decarbonized. A study by Dalla Chiara et al. (2017) considers an energy and usage perspective of sustainable development. The study concluded that HSR is still viable for sustainable development up to 800km.

Sun and Dedoussi (2021) used open aircraft performance models and open ADS-B data to calculate emissions data at a high resolution, namely 2Hz of flight state update rate.

As mentioned previously in subsection 3.2.3, Montlaur, Delgado, and Trapote-Barreira (2021) proposed analytical models to calculate gate-to-gate CO2 emissions and travel time based on the flight distance and on the number of available seats. It found the model to be on par with other CO2 calculators and the grams of CO2 per available seat kilometers was always lower for rail than for air, especially for flights less than 600-700 kilometers.

Noussan, Campisi, and Jarre (2022) gives aside from the LCA overview also a WTW overview, hence this can be partly used for calculating direct emissions.

Source	Key Findings	Conclusions	Relation to this study
European Environment Agency. (2021)	Twenty main city pairs are analyzed WTW, rail travel is always a sensible choice, but the car is worse than air in some cases.	Occupancy rates are very important.	Helps with selecting factors that influence environmental performance, and the selection of policies or actions that can promote environmentally sustainable choices.
B. Wang, O'Sullivan, and Schäfer (2019)	Impact of HSR on reducing CO2 in China is demonstrated, 3-5% of 2015 domestic aviation emissions.	Decarbonizing energy generation (Paris Agreement) leads to even further CO2 emissions reduction. Not taking into account the electricity consumption overestimates environmental benefits.	Necessity to incorporate energy mix of different countries.
Dalla Chiara et al. (2017)	Four Italian routes considered (generalizable all around the world for HSR). Relevance of energy consumption, comparison of travel time and distance, and convenient range determined.	HSR is better than air energy-wise (specific energy gap does diminish as route length is increased). HSR is convenient time-wise to reach the city center and the range is up to 1000 km.	Energy is an important factor as well and needs to be used at least as a base indicator for trains.
Sun and Dedoussi (2021)	Data-driven approach to estimate cruise-level flight emissions over Europe using ADS-B data and openAP emission models.	Open flight data can be used to assess aviation emissions.	Accurate calculation of flight-specific cruise emissions.

Table 3.6: Summary of direct emissions air and rail.

In conclusion, there are many different estimate methods for the different modes of transportation. The importance of checking the drivers and parameters for choosing a particular method cannot be understated. The model ultimately chosen will be adapted to answer the main research question of the carbon difference between the status quo and air-rail intermodality with some uncertainty ranges.

4

Methodology and Preliminary Results

A data-driven approach will be taken. The method is based on a bottom-up approach from individual flights allowing the most accurate results to be found. Figure 4.1 shows the high-level methodology applied. Each section will start with a flowgraph representing a more detailed high-level view of the methodology to arrive at the step-wise results which are explained in more detail in-text.

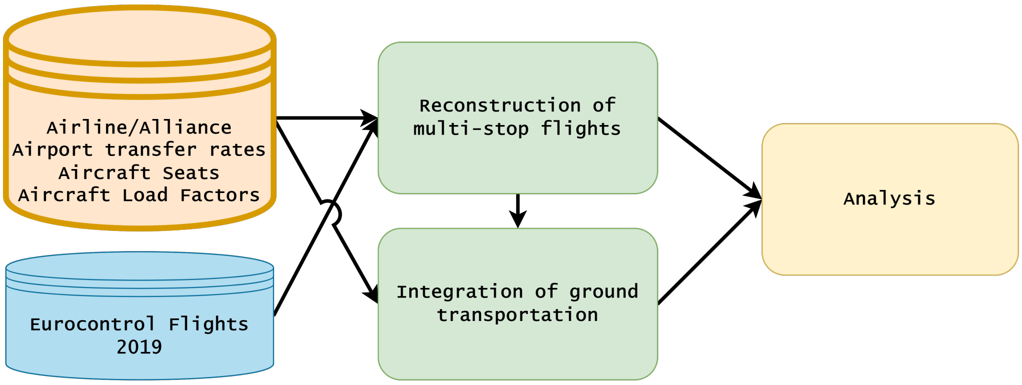


Figure 4.1: The high level methodology.

4.1. Experimental Set-up

This thesis uses a data-driven method that requires the use of memory intensive and at times computationally intensive programs. Eurocontrol's R&D dataset for 4 months of the year 2019 contains about 3.5 million flights which for only 2 legs (smart cross-merge combinations of the post-processed flights) this number quickly adds up and the memory required reaches the limit of a workstation laptop. Pandas the main python package used in this thesis performs all numerical calculations in-memory.

The research question requires ground transportation journeys to compare travel time and carbon dioxide emissions. A practical limitation of this research question is Google Maps Directions API, which has a free usage of 40,000 requests per month.

The technical details used are some python packages, that have proven ability and are commonly used. Pandas is the main workhorse for data analysis and calculation. Matplotlib and Seaborn, for visualization of statistics and data. Numpy, for fast numerical data manipulation and calculations. fastparquet, for saving data in a storage efficient and fast manner. Feather and pickle data format is used when parquet is not applicable. Jupyter is a platform for easier python coding since there are cell-based executions allowing quicker iterations. Also allows for easy documentation with markdown cells. Shapely for geometry calculations.

Collaboration with industry is not a prerequisite, however, it would be good to share the importance of integration. Setting up meetings with high-level people (preferably C-level) across the various industries, government institutions, and the European Commission level with the aim to interview them to find where the obstacles lie in integration. For this appointments have to be made early.

4.2. Reconstructing multi-stop flights

The reconstruction of the multi-stop flights' methodology required breaking the problem up the problem in smaller pieces and solving the individual pieces to come to a complete solution. The reconstruction of multi-stop flights method is visualized at a high level in Figure 4.2. In the figure, the acronym for extract, transform and load (ETL) is mentioned, which covers a variety of processes including data cleaning.

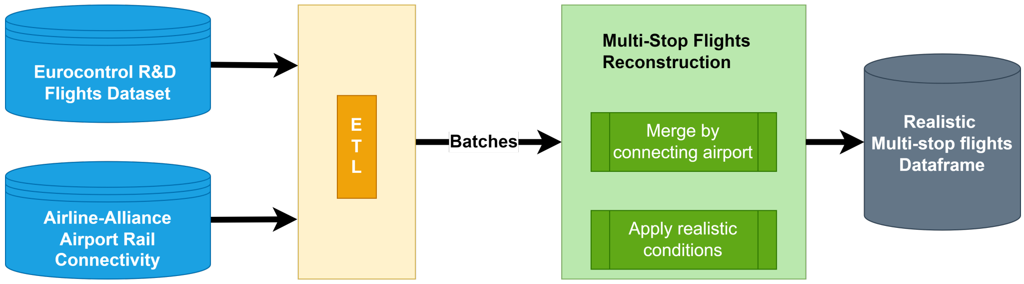


Figure 4.2: Reconstruction of multi-stop flights method.

Inputs and Outputs

In this research, Eurocontrol's R&D dataset[1] for 4 months (March, June, September, December) of the year 2019 will be used as these are the latest months of data available for public use before the COVID pandemic hit. It is therefore apt to cover many future routes and has the most amount of traffic. To supplement this data to be able to solve the research questions and objectives the following data is needed:

- Alliance data, which airline operator works with which alliance. Multi-stop flights can be made up of the same airline for both legs, or the same alliance for both legs (since airlines within the same alliance use codesharing to expand their connectivity). The alliances name each partnering airline on their website which is used as a source of information for this. ()
- Which airports are connected by rail: this can be done using the flights dataset to generate all the airports included in the data and using an online geojson tool[2] to draw polygons around the airports that are most likely connected by rail.

The output is a dataframe of potential realistic multi-stop flights that make up a 2-flight leg journey that passengers would take.

Data processing

The flight dataset processing is used to remove erroneous flights and flights that will not fit the scope of the study. Also, the goal is to supplement relevant information that will be needed later on.

Different techniques are applied. Column renaming, data format correction, the addition of necessary columns (flight time, great circle distances, alliance, connection by rail), cleaning of unknown airport/flight data (ICAO 2022), removal of wrong data (flights that fly less than the great circle distance), keeping only the scheduled airline flights, and unit conversion from nautical miles to kilometers.

- **Airport rail connection**[3] Manually, a polygon that includes all European countries that have ground transportation options in one continuous trip, and inside of the Google Maps API scope (Google 2022) (Google counts an empty response also as a valid request) is created using a geojson map creator (GeoJSON.io 2022). The geojson is then used with the python package Shapely to find airport coordinates that are within the created polygon.
- **Excluded flights:** A condition is made to prevent erroneous flights. For this, the ratio of the actual distance flown divided by the great circle distance is made. The flight is kept if the ratio is larger than 98% but smaller than 120%. This prevents flights that are impossible or diverted.

Multi-stop flights reconstruction model creation

The flight dataset is ready for reconstructing realistic multi-stop flights. Firstly, the potential multi-stop flights are created using the algorithm to be shown here. Secondly, an effort is made to increase their realism of them.

In order to create the potential multi-stop flights, timeslots of arrivals and departures of 1 hour is assigned. The flights are processed in these windows based on the arrivals in a chronological manner going through each hour, day, and month of the dataset. The intermediate results are filtered by 3 simple queries and saved to parquet files to allow future loading without memory constraints:

- Removing multi-stop flights that start and end at the same place,
- or flights that have a different alliance or different operators,

[1] `https://www.eurocontrol.int/dashboard/rnd-data-archive`
[2] `https://geojson.io/`
[3] The rail connection refers to the continuous possibility of using ground transportation commercially speaking between all countries included in the scope.

- or flights that do not have at least one feasible combination of the replaceable leg(s).

The algorithm for finding multi-stop flight combinations of 2 legs is based on an inner merge of the flights of 1 hour of arrivals t^i at airport x and the flights departing that airport in the next four hours after of t^i. This algorithm is placed in a parallel processing pool to speed up the calculation.

The batch of data is then loaded up per month and then the following five realism conditions are applied. The following criteria are created based on the point of view of creating routes that a passenger would realistically take:

- **Worth condition**: the multi-stop flight's direct great circle distance from origin to destination is at least 200 kilometres away. A passenger would not really spend so much time taking a route that is so close.
- **Sense condition**: the total flight's great circle distance should scale based on the direct great circle distance. It does not make sense that someone would take a flight from Madrid, transfer to Beijing and end up in Frankfurt. Using this condition allows real data on multi-stop flights to be used on the overall multi-stop flight instead of single legs.
- **Regularity condition**: There should be at least one flight in each leg every two days from the same airline or the same alliance. Otherwise, the alliance/airline is likely not using that route as a multi-stop flight.
- **Direct condition**: There should not be more than one direct flight every day from any airline/alliance on that route. Otherwise, the passenger is much more likely to choose the direct option.
- **Transferable condition**: The transfer time should be larger than the minimum connecting time (MCT) of 45 minutes and not larger than 4 hours. Otherwise, it is assumed the passenger would not be able to make the connecting flight on-time or would choose a different option. These transfer time ranges are also used in (Jaksche and Asmer 2021), however, the study notes that 45 minutes is a short period for transferring passengers with luggage especially not using the same airline. This is why this method ensures the airline operator remains the same for both flights. The minimum connecting times are given by the airports

In Figure 4.3, the worth and sense condition's great circle distances (GCDs) are visually denoted. Due to the simplistic nature of the conditions, real-world data points could be used from flights found between randomly selected cities in Europe and flights leaving and coming towards Europe. These data points were used to find the ratio between total GCD and direct GCD (GCD_D) which relate to the sense factors and create a polynomial fit to represent the majority of real-world multi-stop flights that are being sold online (sometimes cheaper than the direct flight option). The sense condition values are set by a downward linear line up to 2000 km direct GCD, and a constant value after 2000 km, as can be seen in Equation 4.2. The condition to keep a multi-stop flight is given in Equation 4.3.

$$S = -6.25 \times 10^{-4} \cdot GCD_D + 2.5 \qquad for \quad GCD_D < 2000km \tag{4.1}$$

$$= 1.25 \qquad for \quad GCD_D \geq 2000km \tag{4.2}$$

$$\frac{GCD_1 + GCD_2}{GCD_D} < S \tag{4.3}$$

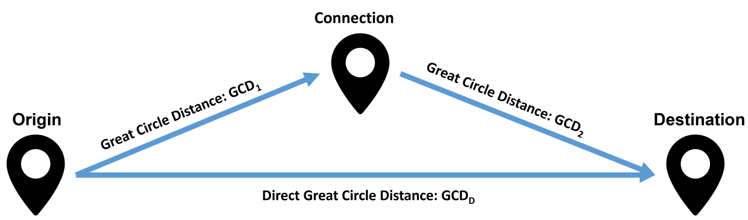


Figure 4.3: Great circle distances between origin, connection and destination.

Aside from this, the category of replaceable multi-stop flight legs[4] is assigned depending on the combination of rail connection of the 3 airports per flight depicted in Figure 4.4:

[4]Replaceability is a term often used which is also not entirely accurate. The flight may not be entirely replaceable, however, it is replaceable in terms of the passengers taking the multi-stop flight could replace the flight leg(s) with ground transportation.

- **Feedrail** is the option where the departing and connecting airport are connected by rail, so the first leg of the 'feeder' flight can be replaced with a feeder rail
- **Endrail** is the option where the connecting and destination airports are connected by rail, so the second flight leg can be replaced.
- **Allrail** is the option where all airports are connected by rail, hence the first and second flight legs can be replaced (either one or both).
- **Bypassrail** is the final (unlikely) case where the origin and destination are connected by rail, but the connecting airport is not. Hence, both flight legs can be replaced by rail.

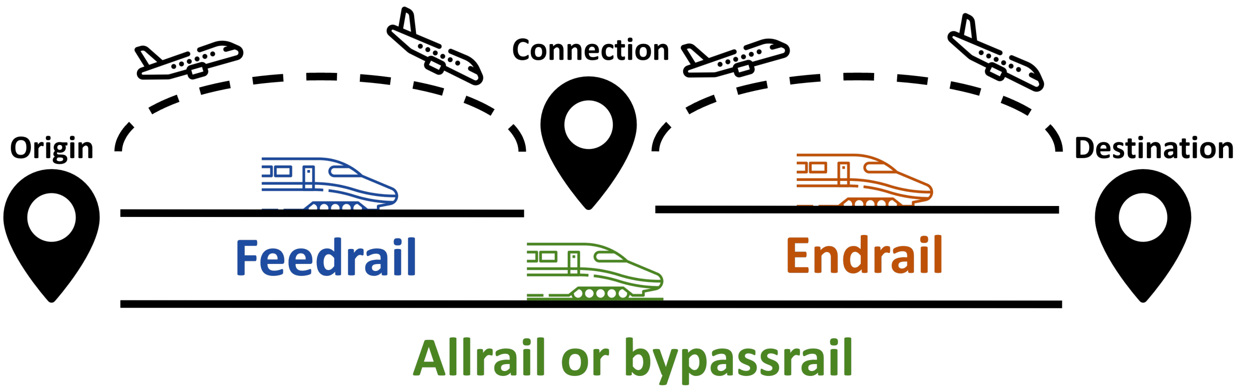


Figure 4.4: The possible combinations of ground transportation integration/replacement between the origin, connection, and destination airports. Namely, feedrail for the first flight leg replaced, endrail for the second leg replaced, and allrail/bypassrail for both legs replaced

4.3. Estimation of multi-stop passengers

In Figure 4.5, the high-level method for estimating multi-stop flight passengers, i.e. passengers that board both flight legs.

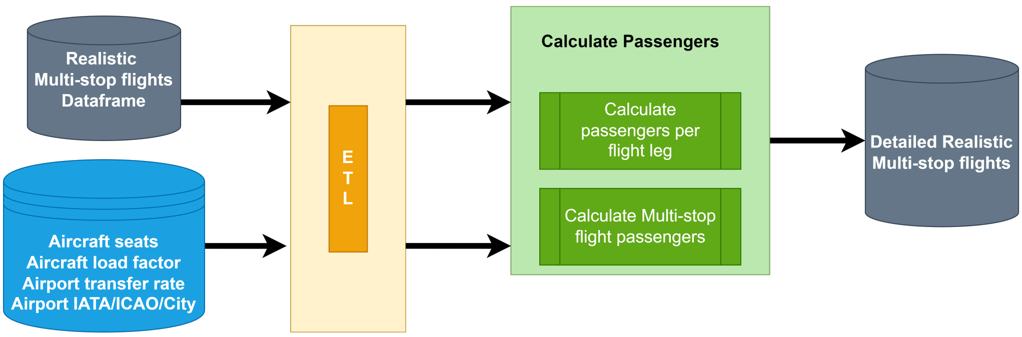


Figure 4.5: Multi-stop flight passengers estimation method.

Inputs and Outputs

The inputs are aircraft data, passenger load factor data, and the dataframe calculated in section 4.2. The output is a dataframe containing estimated multi-stop passengers.

Inputs:

- The realistic multi-stop flight dataframe from section 4.2.
- Data found from aircraft manufacturer websites and others containing aircraft number of seats for single class and two or three class configurations.[5] [6]
- Data on worldwide average passenger load factors are found from IATA (IATA 2022a). The load factor given by IATA is calculated by dividing the revenue passenger kilometer by the available seat kilometers. So it is an aggregate over all flights which gives a good approximation for the average flight load factor.

[5] https://contentzone.eurocontrol.int/aircraftperformance/
[6] https://aircraft.airbus.com/en/aircraft/

- Also, Eurostat contains monthly data of aircraft seats available and passengers onboard for departing flights/passengers for EU28 countries, particularly avia_pao, avia_painc, avia_paexc (Eurostat 2022), which allows calculation of load factors per reporting country.
- Data on airport transfer rates was kindly provided by dr Sven Maertens solely for the use of this thesis (DLR & Sabre 2020; Maertens, Grimme, and Bingemer 2020).
- Data on airport IATA to ICAO codes with regional data is found from Ourairports (Our Airports 2022), which is used to link the IATA code given in the airport transfer rate dataset to ICAO codes used in Eurocontrol's flight dataset. A manual data insertion for some airports without ICAO code's in the OurAirports dataset.

Data processing
The input data are supplemented to the realistic multi-stop flights dataframe. Before the strategies are implemented the passengers in flight leg 1 and 2 separately are calculated by multiplying the load factor with the single class configuration maximum number of seats.

There are several strategies possible to estimate the number of multi-stop flight passengers, i.e., the number of passengers taking both the first and second flight leg. Keep in mind that it is in essence impossible to know exactly the likelihood of a passenger going from A to B and then to C or D. This is because there are many factors at play, for example, socioeconomic factors, seasons, geopolitical, traveler choice, etc. The best that can be done is an estimate because this data is kept confidential by airlines. The transfer passengers are simply calculated by multiplying the first flight leg passengers with the airport transfer rate. The number is made into integer numbers to prevent 1.1 transfer passengers. The transfer passengers moving to that particular second flight leg are calculated using a likelihood number. The following strategies are implemented in this study to calculate this likelihood:

- Splitting the passengers depending on the ratio of the flights' total **remaining** passengers (possibly the previous transfer window has already filled the flight) to the total number of **remaining** passengers in all flights in the connecting flight's window.
- Splitting the passengers depending on the transfer times, lower transfer times lead to higher likelihoods.
- If the same destination is possible multiple times in the same transfer window, the first possible flight is filled completely.
- Splitting the passengers evenly among the flights.
- Splitting the passengers depending on the monthly passenger city pairs statistical data.
- Splitting the passengers depending amount of hours of flight leg 1. I.e. if a passenger already spent 10 hours on a flight it is likely the destination is nearby.

For the preliminary findings only strategy 1 is implemented. This is for two reasons; it is looking at it from a passenger's perspective and completely distributes passengers. For the final report an evaluation of each strategy separately or a combination of some strategies will be looked at. The strategy number 1, splitting the total number of passengers in the connecting flight windows, is implemented using the following steps were taken:

1. The realistic multi-stop flights dataframe is sliced down to the flight ids of the first flight leg and the number of passengers in the second flight leg, a groupby of the first flight ids is performed and the sum is taken.
2. The resulting dataframe contains the flight leg 1 ids by the total number of passengers in the possible flight leg 2. For example, if flight leg 1 had 5 possible connecting flights, each with 200 passengers. Flight leg 1 would have 1000 total number of passengers in possible flight leg 2.
3. Then the likelihood of flight leg 1 passengers moving into flight leg 2 is the number of passengers in flight leg 2 divided by the previously calculated total number of passengers in the possible flight leg 2, which is 0.2 or 20%.

Finally, the output is the estimated multi-stop flight passengers added to the input dataframe. This column is calculated by multiplying the airport transfer rate with the passengers in flight leg 1 and the likelihood calculated previously.

4.4. Ground transportation journey

In this section, the integration of ground transportation within a multi-stop flight journey is explained. The goal is to replace one or more flight legs with ground transportation if the total extra travel time is below a predetermined time.

In Figure 4.6, the high-level method for generating ground transportation journeys is shown. The key performance indicators (KPIs) are generated to extract value from the ground transportation journey response.

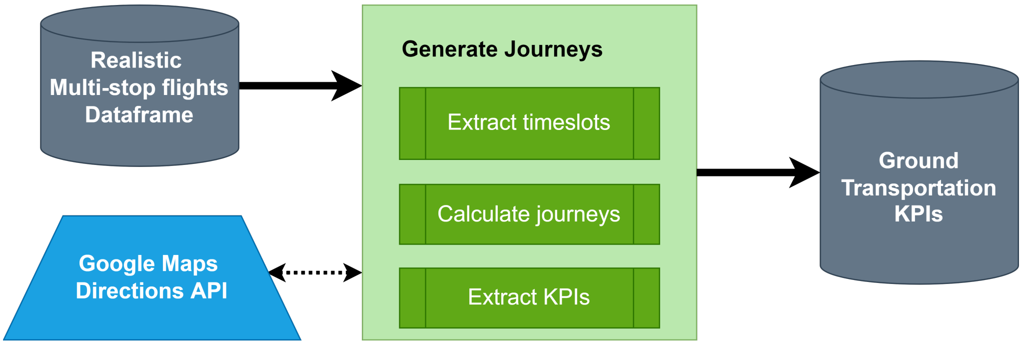


Figure 4.6: Ground transportation journey calculation method.

Ground transportation arrival and departure times estimation

The realistic multi-stop flight data is used as input to create estimated ground transportation arrival times for feedrail and departure times for the other types.

This is done by creating timeslots of one hour per flight. In the case of feedrail, the ground transportation must arrive at least before the airport's kerb to gate time and some buffer. To have enough data for a range of arrival times, the arrival times are set to 2, 3, and 4 hours before the off-block time (when the aircraft leaves the gate) of the second flight leg. For the other types of ground transportation replacement, the time constraint is not existent. However, the waiting time should be reduced for endrail, so 1 hour is added to the arrival of the first flight leg's timeslot. This accounts for the airport's gate to kerb time.

In total two dataframes are created. The arrivals dataframe consists of feedrail and the first leg of allrail. The departures dataframe consisting of endrail, the second leg of allrail, and the departing and destination airport of allrail and bypassrail multi-stop flights.

Ground transportation journey calculation

The timeslots calculated are loaded for the calculation of the ground transportation journey.

Google maps directions API is used to calculate the ground transportation journey. The inputs of the API are the origin location which is the departure airport, and the destination location which is the destination airport. The airport locations are used as it is assumed to be the best possible approximation of a comparative ground transportation journey, whilst limiting the required API requests. Also, the mode of travel is set to transit mode with the preferred transit mode set to train. Also, alternatives are set to True which gives 4 different options at no extra requests. The unit is set to metric.

An important option is the option of arrival time or departure time is set as well depending on the replaceable flight leg category. In the case of feedrail the ground transportation must arrive on-time to go from the airport's kerb to the gate. These kerb to gate and gate to kerb times are from the DATASET 2050 dataset.

The output of the API will dump pickle files into the corresponding departures/arrivals folder. Also, some metadata is saved such as the given inputs, and whether the response was successful.

Ground transportation journey KPI extraction

Google maps API response contains plenty of data.[7] Not all of this data is needed, and the memory constraints limit the amount of data in memory at any moment in time. Hence, the data is split into halves and the JSON response is normalized to allow the extraction of KPIs. For the purposes of this thesis, the following KPIs are extracted:

- Distance per country traveled by rail: this is important to calculate rail emissions.
- Total train stops
- Total train/road/walking distance traveled, separately
- Total walking distance at the destination airport
- Total transfer time

[7] https://developers.google.com/maps/documentation/directions/get-directions

- Total train stops
- Departure/arrival time
- Total ground transportation time/distance

The method to extract these KPI's is, in essence, extracting fields from a dictionary and applying some simple calculations with the exception of the distances per country because this is calculated from a polyline object. This polyline represents a set of coordinates in a string format developed by Google. It is useful to reduce the disk size because the coordinates are very tightly packed (at times 0.1m apart).

A python package called polyline is used to decode the string back to a list of coordinates to a list of tuples of coordinates. Once the total list of tuples of coordinates is made the haversine function is used to calculate the distance between each coordinate and a python package called reverse geocode is used to find the country ISO adding it to a dictionary with the country ISO's as keys and the distances per country calculated and summed as the value per country key. Reverse geocode has an issue with newer python version which can be fixed.[8]

Due to the sheer size of the uncompressed polylines, a chunking algorithm is made to chunk the data into eights and saving intermediate results. Once the intermediate result is saved, the memory is cleared and the next chunk is loaded in. The output is all the KPIs needed to compute travel times and carbon emissions of ground transportation.

4.5. Intermodal transportation integration

In Figure 4.7, the high-level method for integrating the multi-stop flights with the ground transportation KPIs is shown.

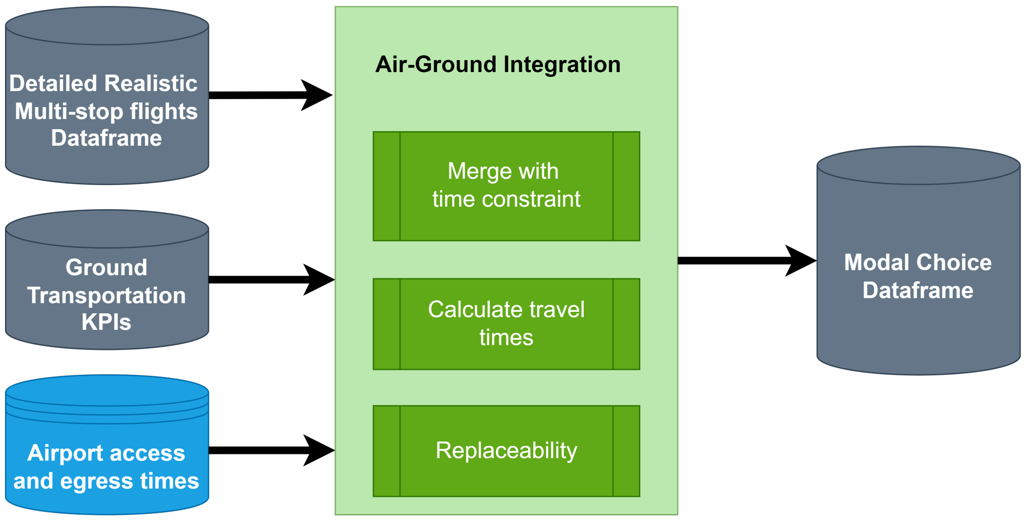


Figure 4.7: Ground and air intermodal integration method.

Inputs and outputs

The detailed realistic multi-stop flight with passenger data is loaded together with the KPIs from the ground transportation journeys. The output is a dataframe with the data required to compare the travel time between a multi-stop flight and an intermodal journey.

Integration

The pandas asof merge algorithm is used to merge travel times with a tolerance, i.e. to the nearest key instead of equal keys. For instance, in the case of feedrail take a ground transportation arrival time of 6:31 pm and a necessary arrival time for a connecting flight of 6:49 pm. If the tolerance is 20 minutes, this merge would be successful depending on the direction of the merge.

There are three possible directions of merge as of: backward, forward, and nearest. As the names suggest they handle the selection of the tolerance depending on the location of the keys. Backward for instance selects the last row in the right dataframe whose on key is less than or equal to the left's key.

[8] change line 74 of __init__.py to: rows = csv.reader(open(local_filename, 'r', encoding="UTF-8"))

Category	Type	Time	Direction
Feedrail	Arrival	FOBT_y_KG	backward
Endrail	Departure	FAT_x_GK	forward
Allrail	Departure	FOBT_x	nearest

Table 4.1: Merge as of options for the integrated ground transportation categories

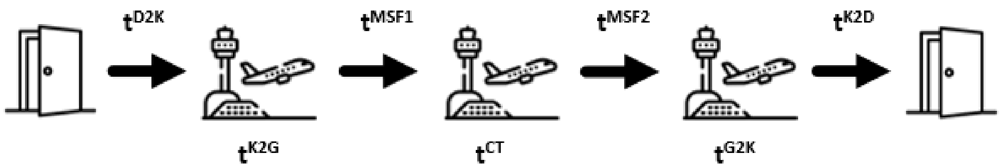


Figure 4.8: The door to door travel times for multi-stop flights.

It is chosen that the left keys are the multi-stop flights and the right keys are the ground transportation journeys. For feedrail it is important that the direction is backward, that way the ground transportation arrival time is not after the time required to enter the airport. For endrail the direction must be forward to ensure the exit of airport before starting the ground transportation journey. For allrail there is no time constraint so the nearest direction is set. Table 4.1 shows the different merge as of options between the categories.

Travel time calculations

The total travel time for multi-stop flight and ground transportation is calculated separately by looking at it from a door-to-door approach, as shown in Figure 4.8 for multi-stop flights.

For intermodal transportation the total travel times are calculated depending on the category of replaced flight leg. The ground transportation total travel times are calculated the same way as the multi-stop flights, but removing certain times which are not present for ground transportation.

- The feedrail removes the first flight leg (including the connecting flight transfer time) and the airport's door to kerb time.
- The endrail removes the second flight leg (including the connecting flight transfer time) and the airport's kerb to door time.
- Allrail or bypassrail skips both legs, so only the ground transportation journey time remains.

A flight leg is considered replaceable if the total travel time intermodal travel journey (or ground transportation journey in the case of allrail or bypassrail) minus the multi-stop flight total travel time is larger than or equal to the maximum extra travel time set.

The flights from allrail which are not replaceable are fed into a similar algorithm to find first feedrail possibilities, and the ones from these that are not replaceable are finally tried for endrail. To ensure flight IDs are not duplicated for the analysis, the duplicates are dropped. To keep the important flights first the dataframes are concatenated in priority of replaceable allrail flights kept first.

Preliminary Implementation

The previous sections including this one have been implemented, the following sections are yet to be implemented. These will be implemented for the final report.

4.6. Emissions estimation

In Figure 4.9, the high-level method for estimating emissions for the different modal choices is shown.

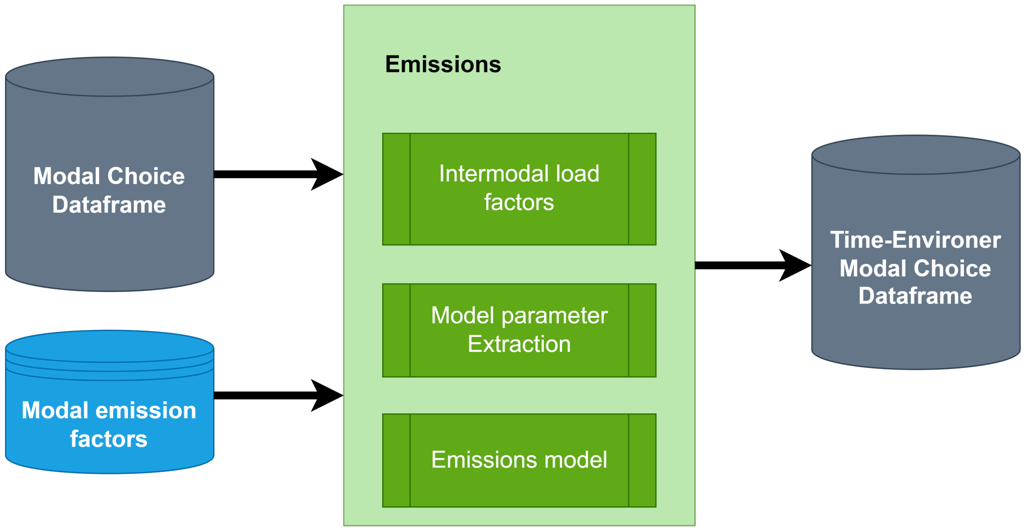


Figure 4.9: Estimating carbon dioxide emissions method.

The estimation of emissions for the different modes of transportation will be done on a per-passenger kilometer basis using average emission rates from different modes of travel and applying uncertainties. Several studies have been done on estimating emissions of different travel modes in Europe (Noussan, Campisi, and Jarre 2022; Fraunhofer ISI and CE Delft 2022; European Environment Agency. 2021). For rail and aviation particularly, a more accurate estimation will be done if possible. For rail, the country's average gCO2/kWh[9] is used together with train occupancy, distance, and the number of stops to have a more realistic estimate of the energy usage and hence gCO2 produced per passenger. For aviation, the load factor, flight distance, and flight time, will be used to estimate the emissions per passenger for a particular flight. For other modes, the default indicator gCO2/pax/km is used to have an idea of the emissions. Uncertainties in the parameters will be used to reflect the uncertainty in the outcome.

4.7. Simulation

The previous methods described will be placed in a simulation environment to create a range of possible outputs to verify the multi-stop flights. A bottom-up approach is used to simulate, for example, 1 million passengers with random origins and destinations and origins.

The simulation will allow for assessing the realism of the methods, but also the effect of missing a connecting train.

4.8. Sensitivity analysis

Sensitivity analysis will be conducted to examine the sensitivity of the output to changes in parameter values. This will allow measuring the uncertainty of the output to different sources of uncertainty in the initial parameters. Local sensitivity analysis will be the first step in understanding how a single parameter changes the model output. Then, contour plots will allow an analysis of parameter interactions for important parameters.

The uncertainties will be incorporated into the model to allow for ranges of outputs.

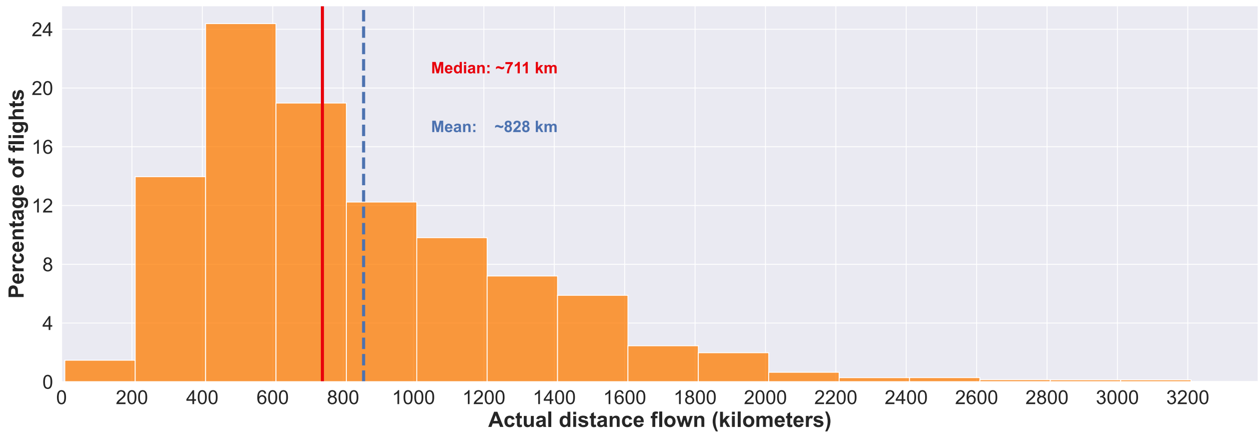
[9] https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1

5
Preliminary Analysis

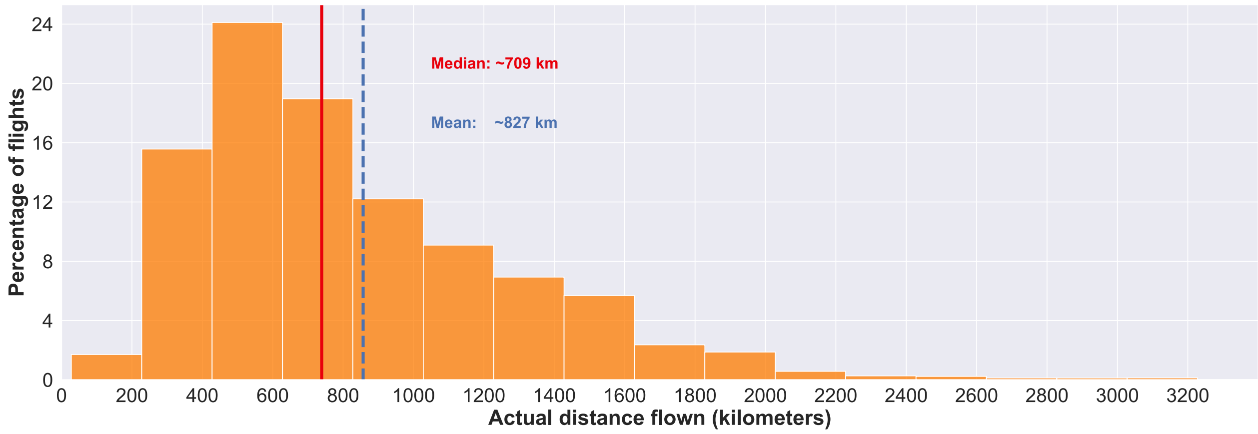
This chapter brings forth the graphical results from the implementations described in chapter 4. The results are analyzed and related to the research questions to give a preliminary answer.

5.1. Analysis of the single flights dataset

In Figure 5.1, the Intra-European[1] single flights are shown, which are in essence the possible flight legs replaceable for multi-stop flights. Note that only traditional scheduled flights are considered, which consist of about 50% of the flights in 2019 (EUROCONTROL 2022b). As can be seen in the two figures, both years are similar and more than half of the yearly flights are below 710 kilometers. From now on only the year 2019 will be considered due to the similarity.



(a) Intra-European flights in 2018. Median lies around 711 km, mean around 828km and around 1.67 million flights total.



(b) Intra-European flights in 2019. Median around 709 km, mean around 827km and around 1.69 million flights for 2019.

Figure 5.1: Percentage of intra-European single leg flights composition per 200 kilometer intervals for intra-European flights with ground transportation connection from March, June, September, and December of 2018 and 2019.

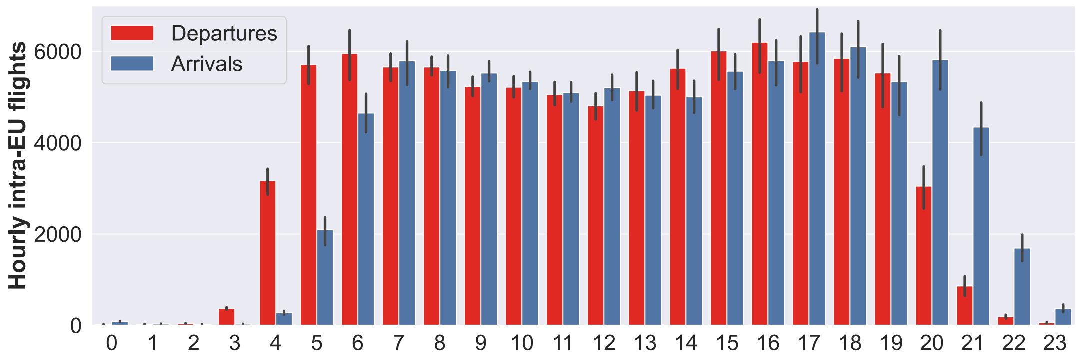
[1] The EU, European, and Europe are used interchangeably. To be geographically/politically correct the data presented uses the phrase intra-European as the explanation given in the methodology in section 4.2 to flights departing/arriving from airports connected to ground transportation.

For Figure 5.2a, one can notice that flights departing range mostly from 4 am to 8 pm. And flights arriving start one hour later (suggesting the average flight time to be at least one hour) from 5 am to 9 pm. Notice the peaks occurring throughout Europe early in the morning (7 am-8 am) and late in the afternoon (4 pm-6 pm), however, the distribution throughout the day is about the same as aircraft take-off and land at the different airports somewhat levels it out.

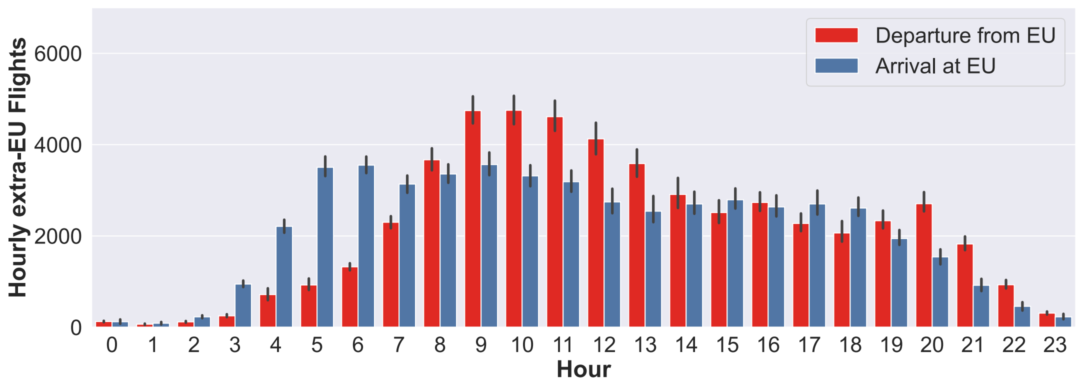
For Figure 5.2b, the large peak of departures from the EU from around 9 am-1 pm gives the clue that most feedrail possibilities are around this time. Whereas endrail possibilities are spread throughout the day. No information for allrail can be described from this graph as allrail is by nature intra-European.

Looking at the times from a multi-stop flight journey perspective allows a more complete analysis. For feedrail and endrail, Figure 5.2b is perfect for this analysis. The arrival times will be important for replacing the final leg of the journey, or endrail, as the ground transportation journey starts after arriving from the connecting flight and skipping the departing flight leg 2.

For allrail the departing time is important as the departing time in this study sets the departure time of the ground transportation journey. This might be a drawback to the algorithm as it might be the case that ground transportation is weaker in the off-peak hours during the day. So, it might be better to find a more convenient time to use allrail, using some iterations. This might reduce the total travel time, at the expense of having a somewhat different arrival/departure time. So, it is likely the algorithm will change to do some iterations based on the preliminary findings, especially for allrail time merging. This would also reduce the number of requests as only a few timeslots between airport pairs must be calculated. For feedrail the departure time of the second flight leg is important as this is the time the ground transportation must arrive before to allow for boarding of the aircraft. Hence, the departure times from Figure 5.2a suggest that there are many early morning flights that are likely not able to be served from feedrail as it would probably have to start by the end of the previous day. This is an interesting point of operational improvement for airlines aiming to have intermodal integration, understanding the catchment area of the airport with HSR connection, and coordinating the timetables to allow for at least a higher likelihood of integration.



(a) Intra-European flights departure and arrival times in intervals of 1 hour. Errorbars represent the weekday variation.



(b) Hourly departures and arrivals from and to Europe with intervals of 1 hour and errorbars represent the weekday variation.

Figure 5.2: Single leg flights in Europe departure/arrival times. Cumulative numbers from March, June, September, and December 2019.

In Figure 5.3, there is a growing relationship between distance and time. The marginal histogram plot on the top of the x-axis is similar to the one in Figure 5.1. One observation that can be made, however, is that there are many outliers as can be seen in the different levels of the kernel density estimate in red. Some flights that are 500 kilometers can take as much as 2 hours, while the majority lie around 60 minutes. This is also seemingly the most common flight time, about 60 minutes. These long flight times, but short distance flights are especially replaceable in a multi-stop flight journey. Imagine the pullback and taxi time to Schiphol's Polderbaan consists of almost half of the "flight time".

To find out the reason for the outliers, it would be interesting to see the effect of time of day on delay as a possible explanation. This is however out of the scope of this study. But, it would be interesting to analyze if intermodal integration's reduction of flight, if utilized, would have a significant and measurable effect on the reduction of flight delay to congestion.

For policymakers, the great circle distance might be a better indicator than the flight distance for relating to city pairs or airport pairs. Note that the flight distance saved is the actual flight distance for the respective categories.

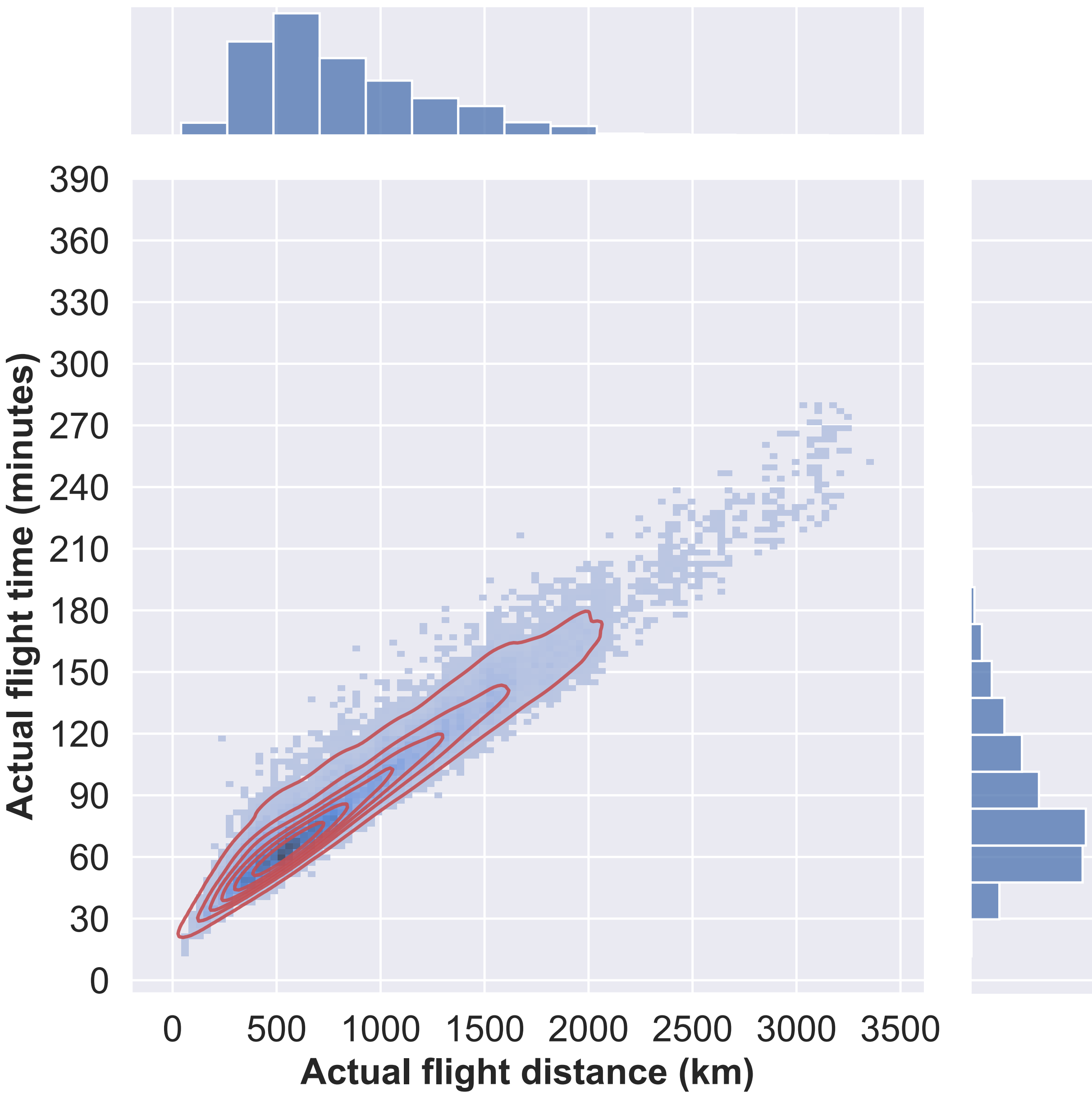


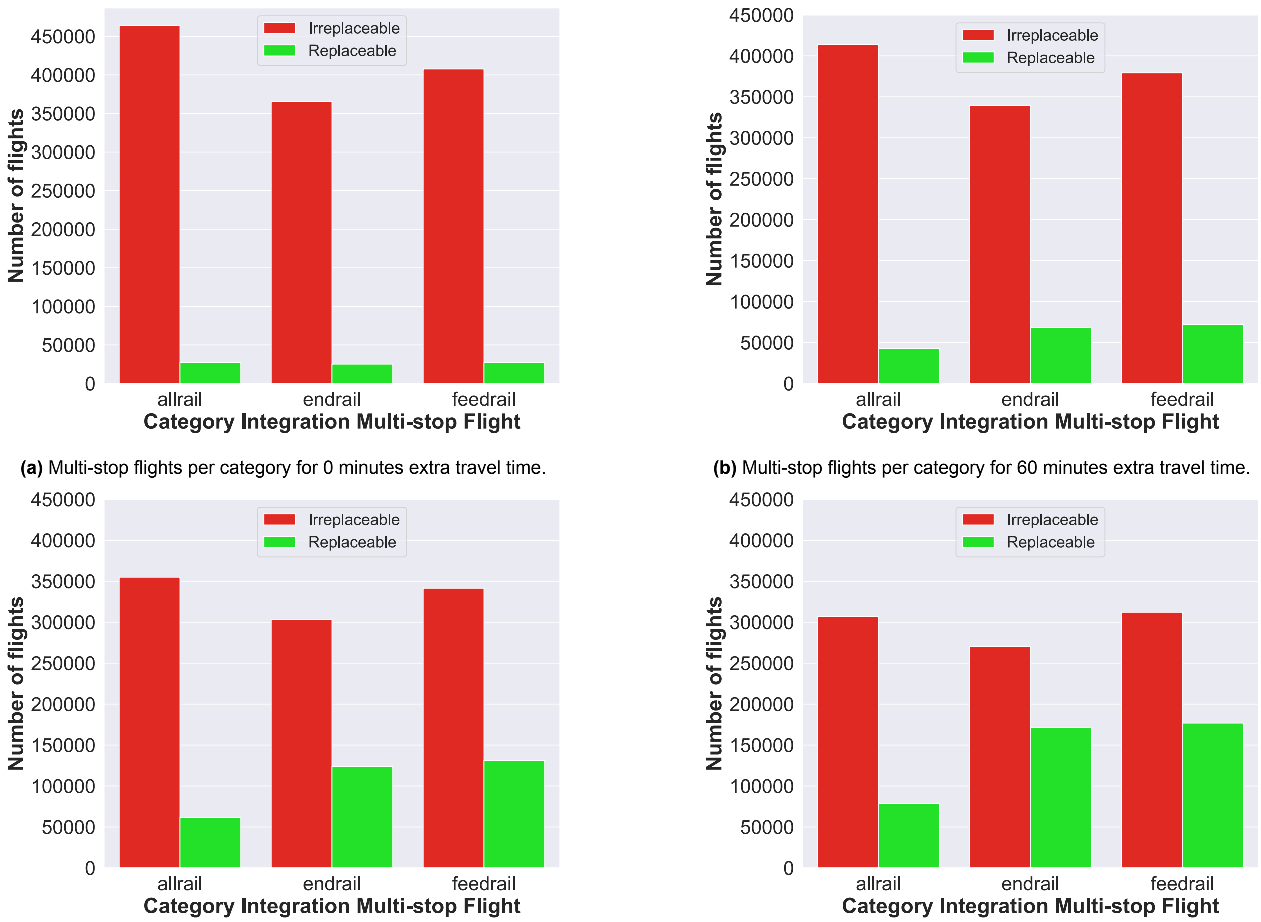
Figure 5.3: Relationship between actual flight distance and actual flight time for single leg intra-European flights in 2019. Cumulative data from March, June, September, and December 2019.

5.2. Analysis of multi-stop flights results

The growth in replaceability shown in Figure 5.4 is clear when increasing the extra door-to-door travel time. What is interesting to note is the rate of increase between allrail[2] and feedrail/endrail. From 0 to 60 extra travel time, all categories start at about 25 thousand flights replaced each at 0 extra travel time. Allrail increases by 100%, doubling when considering 60 extra door-to-door travel time. Endrail and feedrail increase by almost 150%. For the growth between 60 and 120 extra travel time the growth of allrail decreases to about 50%, half of the previous growth. The growth of feedrail/endrail decreases to about 110%. Finally, from 120-180 extra travel time the growth of allrail is about 25%, also half of the previous growth. Feedrail/endrail growth decreases to about 40%, more than halving the previous growth.

One cause for the larger growth feedrail and endrail is the algorithm used and the priority of categories. The algorithm tries to find replaceable flights for feedrail, endrail, and allrail separately at first. Then, the allrail flights that were not replaceable are fed in again for feedrail, and the remaining flights that are not replaceable are then fed into endrail. Notice that the total allrail flights decrease from around 450 thousand at 0 extra travel time to 350 thousand at 180 extra travel time. However, as the runs are done separately four times, the rate of growth cannot be explained in this way.

The realistic conditions reduce the total number of multi-stops significantly. Tuning the parameters for the worth, sense, regularity, and direct conditions, during the sensitivity analysis will allow a better idea of the effect of the conditions on the number of multi-stop flights.



(a) Multi-stop flights per category for 0 minutes extra travel time.

(b) Multi-stop flights per category for 60 minutes extra travel time.

(c) Multi-stop flights per category for 120 minutes extra travel time.

(d) Multi-stop flights per category for 180 minutes extra travel time.

Figure 5.4: The distribution of potential multi-stop flights per category. Irreplaceable means no flight legs can be replaced for a passenger below the stated extra travel time.

Allrail is trying to replace two flights, which means a lot of time savings at the airport. When replacing a single leg it is more likely that it is a domestic connection being replaced, hence leading to better connections. This is because European rail operators optimize rail connections for regional connections and less so for international connections with regional connections. Geography and the inefficiencies of ground transportation

[2] allrail includes bypassrail as it represents a very small number (order of 10^3) of flights.

at longer distances, and for crossing multiple borders at the moment cause a sort of limit of growth. Operationally, international train operators can improve this by improving the coordination of time schedules between international routes.

Finally, the algorithm for allrail can be improved leading to more realistic travel times (and possibly more replaceability) by making it more door-to-door with 2 methods:

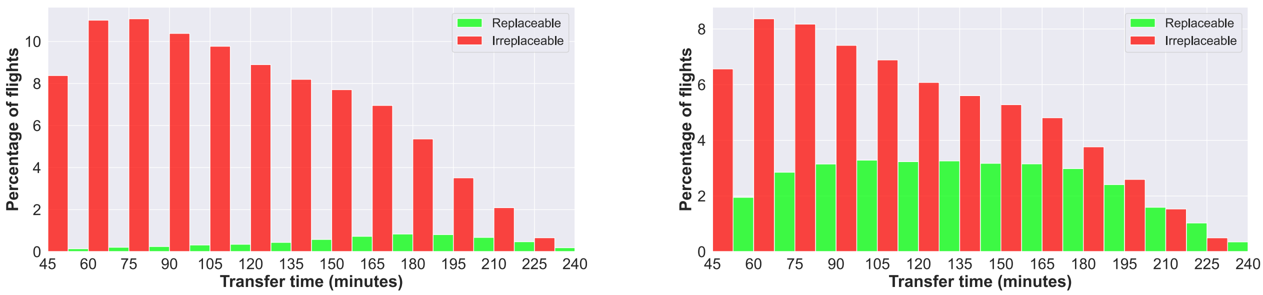
- Instead of the departing and destination locations being the airport, use the most nearby city as a reference. Many airports are bad modal hubs which might add extra hours since there are two airports that are egressed and accessed for allrail.
- Choosing better transit times, departing early in the morning regardless of the original flight's time.

Similarly, for endrail the final destination can be the city next to the destination airport. And for feedrail the departing point can be the city next to the departing airport.

Of course, it really is a passenger choice that factors in the amount of extra door-to-door travel time acceptable, and the type of passenger influences the airport access and egress times as shown in Dataset 2050 [3]. This is definitely an interesting topic for future research, how the passenger type and choices affect the result.

In Figure 5.5, for brevity, only 0 and 180 extra travel time is included. As can be seen, the transfer times are limited from 45 minutes to 4 hours as was defined during the reconstruction of realistic multi-stop flights.

As expected the transfer time influences the replaceability significantly. The lower the transfer time the least amount of replaceable flights. This means that if the transfer times increase over time due to congestion, or reduced frequency, it is clear that intermodal transportation will become more advantageous.



(a) Transfer times and replaceability for 0 minutes extra travel time.

(b) Transfer times and replaceability for 180 minutes extra travel time.

Figure 5.5: Transfer times of connecting flights.

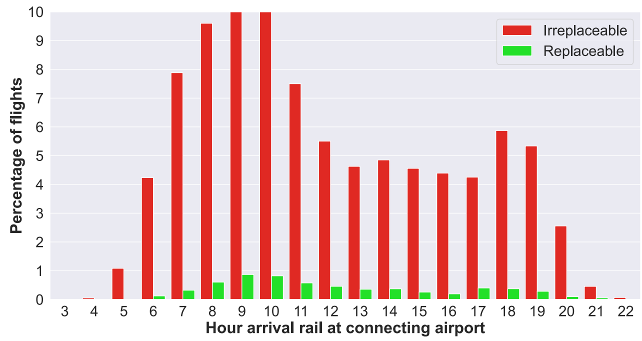
In the three figures that follow, Figure 5.6, Figure 5.7, and Figure 5.8 the departure or arrival time of ground transportation, or rail, is related to the replaceability to derive some understanding of the effect of time of day on replaceability. This is done by comparing the 0 minutes of extra travel time to 180 minutes of extra travel time. Also, every category is looked at separately.

Endrail:
For endrail given in Figure 5.6, the peak multi-stop flight connections occur around 6 am-7 am. It is unclear which is the best time. However, it is clear that the worst times for endrail are early in the morning before 6 AM and in the afternoon after 4 pm.

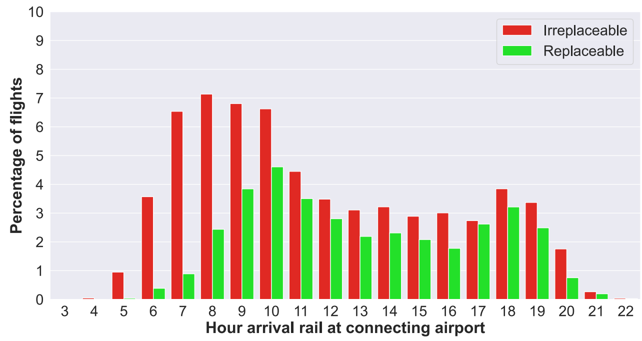
Feedrail:
For feedrail shown in Figure 5.7, the arrival times between 1 PM and 6 PM seem to be the best. The peak times that there are connecting flights occur from 9 am-1 pm leading to sub-optimal performance of ground transportation. It is clear that many early flights require incredibly early ground transportation journeys, which reduce the catchment area and replaceability significantly. Here most of the operational recommendations can be made as it is clear that the peak feedrail possibilities are not replaceable due to the earliness of the journey. Moving the second flight legs to noon time would increase the possible replacements.

Allrail:
For allrail given in Figure 5.8, the best time for departures seems to be from 6 AM to noon time. This makes sense as ground transportation works well at these times due to normal commute times.

[3] http://visual.innaxis.org/dataset2050/d2d-time-distribution/

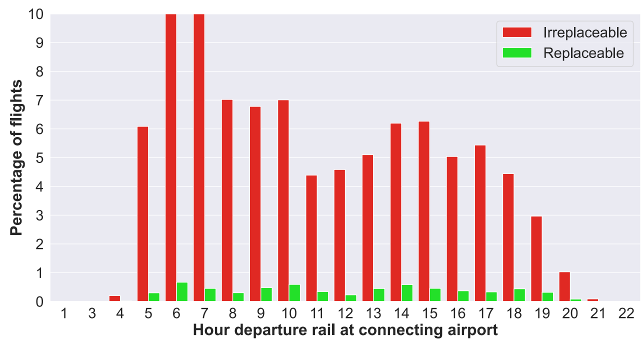


(a) Departure time versus % of replaceable endrail flights for 0 extra travel minutes.

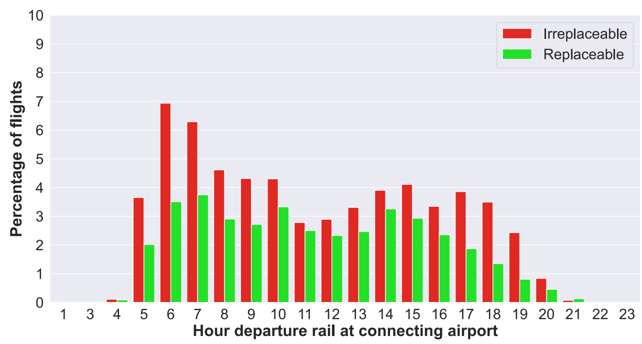


(b) Departure time versus % of replaceable endrail flights for 180 extra travel minutes.

Figure 5.6: Departure time of rail at connecting airport for endrail flights.

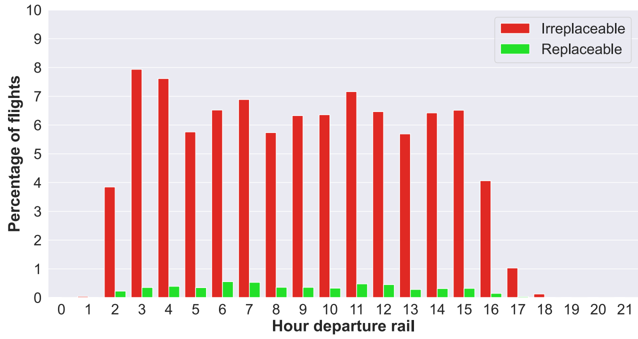


(a) Departure time versus % of replaceable feedrail flights for 0 extra travel minutes.

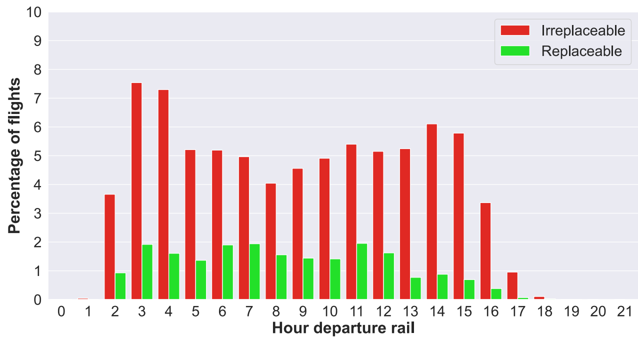


(b) Departure time versus % of replaceable feedrail flights for 180 extra travel minutes.

Figure 5.7: Departure time of rail at the connecting airport for feedrail flights.



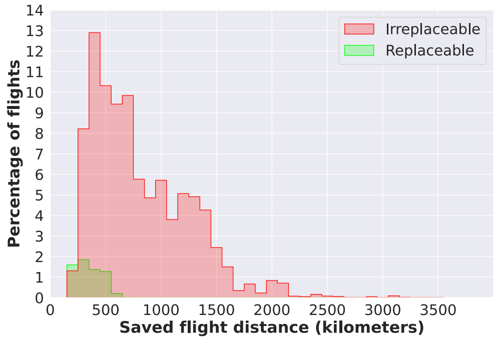
(a) Departure time versus % of replaceable allrail flights for 0 extra travel minutes.



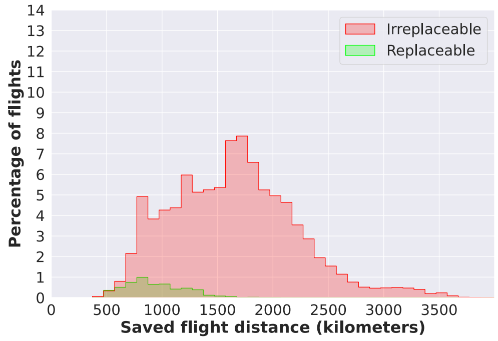
(b) Departure time versus % of replaceable allrail flights for 180 extra travel minutes.

Figure 5.8: Departure time of rail at the departure airport for allrail flights.

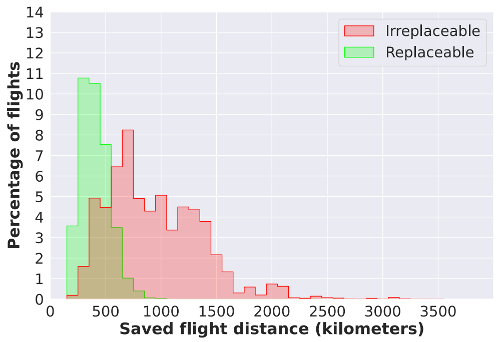
In Figure 5.9, a histogram plot is shown to understand the distances that ground transportation is able to compete in terms of travel time versus air transportation. It is split between feedrail/endrail and allrail for clarity and analysis. Logically, the growth for shorter distances is clear. As mentioned previously inefficiencies in transfers across borders lead to a bottleneck the further the distances become.



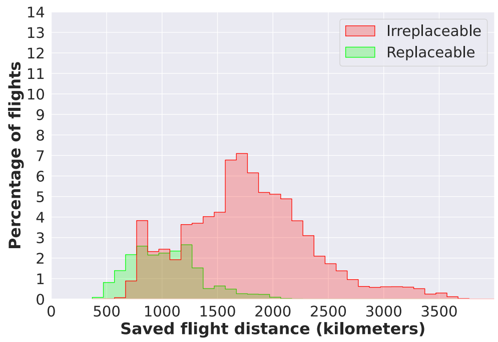
(a) Feedrail/endrail replaceability for 0 minutes extra travel time.



(b) Allrail replaceability for 0 minutes extra travel time.



(c) Feedrail/endrail replaceability for 180 minutes extra travel time.



(d) Allrail replaceability for 180 minutes extra travel time.

Figure 5.9: The actual distance flown that would be saved in intervals of 100 km and percentage of all multi-stop flights per category replaceable.

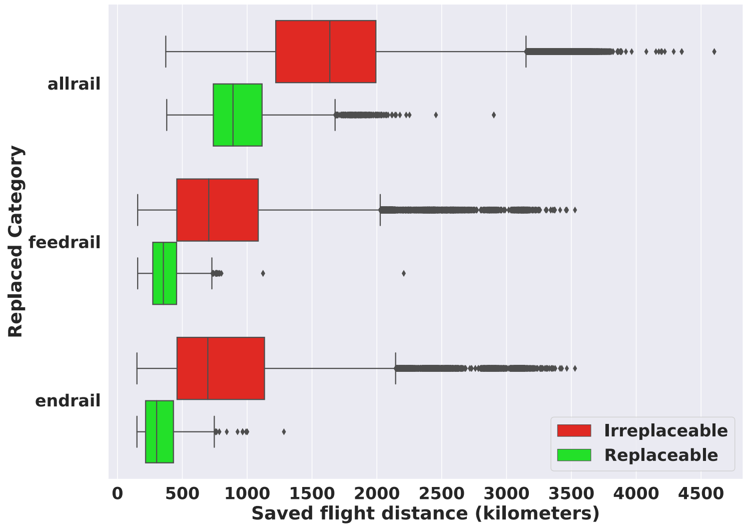
In Figure 5.10, boxplots are shown to show the statistical distribution of the previous figures on saved flight distance in relation to replaceability allowing for further analysis.

One can notice that the median flight distances for the irreplaceable flights of feedrail/endrail in Figure 5.10a are similar to the ones found in Figure 5.1, and about twice as much as the ones for allrail. However, it is somewhat shifted to the right. This is because the remainder of the irreplaceable flights tends to be long-distance flights. It is shown clearly when comparing the figure with the extra travel time of 180 minutes, in Figure 5.10b.

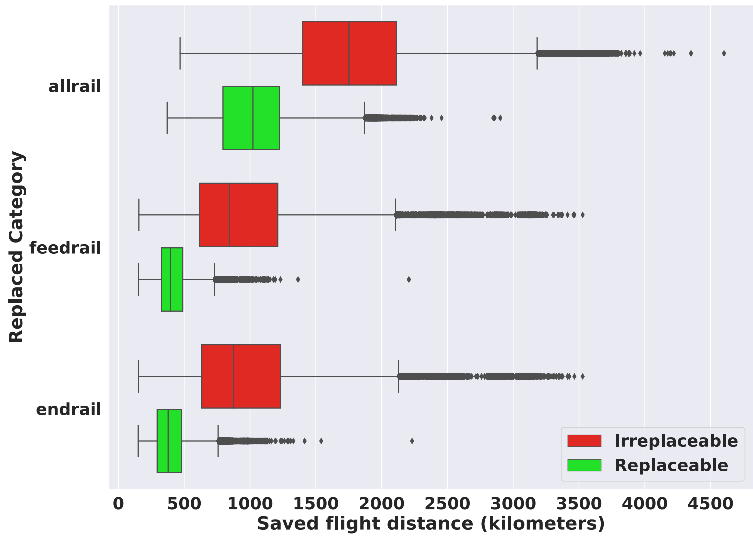
A remarkable finding is that ground transportation can offer better travel times for allrail up to 2000 kilometers, surpassing many of the estimates found in the literature review. For feedrail/endrail it can only be competitive in terms of travel time up to about 750 kilometers for 0 minutes extra travel time, and 1250 kilometers for 180 minutes extra travel time. This is on the high-end of literature replaceable ranges, surpassing many estimates as well.

To best depict the number of replaceable flights depending on extra travel time a jointplot is made and shown in Figure 5.11. The large portion of flights that can be replaced easily is until about 180 minutes extra travel time. After this not many more flights can be replaced unless a huge increase in travel time is made.

Because of all the rail infrastructure projects, and the intermodal transportation projects and initiatives, it is expected that this extra travel time will decrease over time and will push the boundary a bit lower so there will be a larger amount of flights replaceable in the upcoming years and decades.

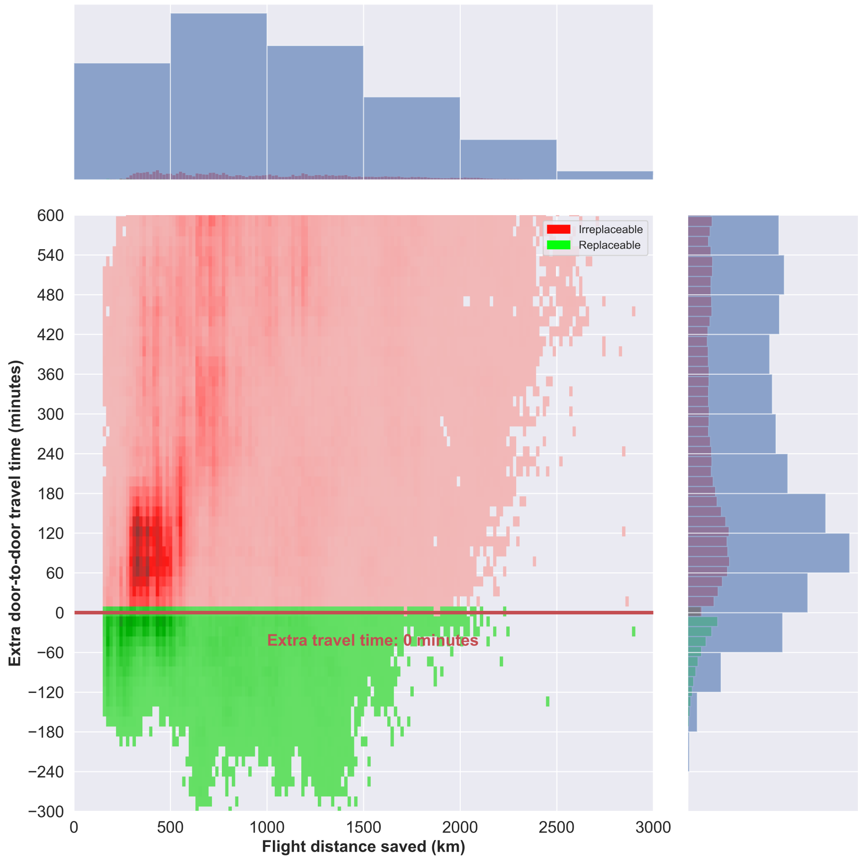


(a) Actual distance flown distribution based on replaceability and integration category for 0 minutes extra travel time.

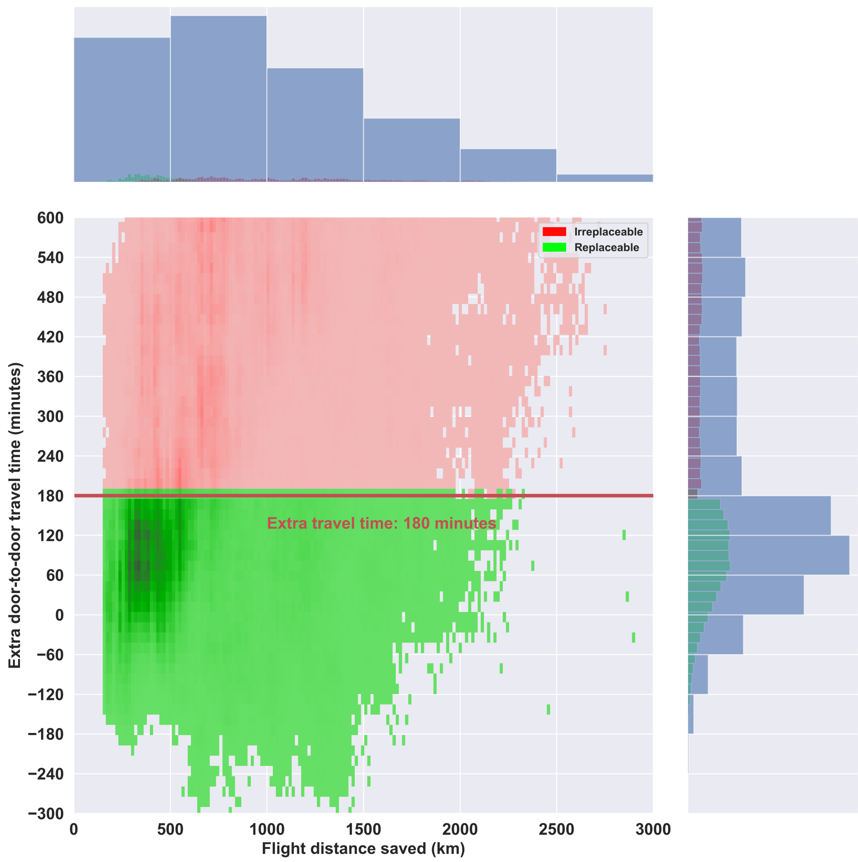


(b) Actual distance flown distribution based on replaceability and integration category for 180 minutes extra travel time.

Figure 5.10: Boxplots of actual distance flown replaceability based on integration category.



(a) Actual distance flown and extra travel time for 0 minutes extra travel time.



(b) Actual distance flown and extra travel time for 180 minutes extra travel time.

Figure 5.11: Actual distance flown versus extra travel time. Hue's provides the reference on replaceability and a line is made to denote the maximum replaceable extra travel time set.

6 Planning

In Figure 6.1 the research framework from Figure 2.1 is adapted to show the current state of progress at the preliminary and what is yet to be done for the final report. Also, a Gantt chart was created for planning purposes. The Gantt chart planning tried to be as complete as possible regarding free days off. The planning includes public holidays, limiting weekends, including a 2-week vacation in December, etc. Furthermore, personal milestones are set as well as official milestones. For example, every progress meeting is a time to validate the work and summarize results. Also, delivering skeleton versions of key milestones such as the preliminary report, green-light review, and a draft of the thesis paper. The planning largely follows the goals set by research sub-goals. Also, the research framework is used for the planning. But it also includes coding tasks and iterations to account for failures or subsequent runs.

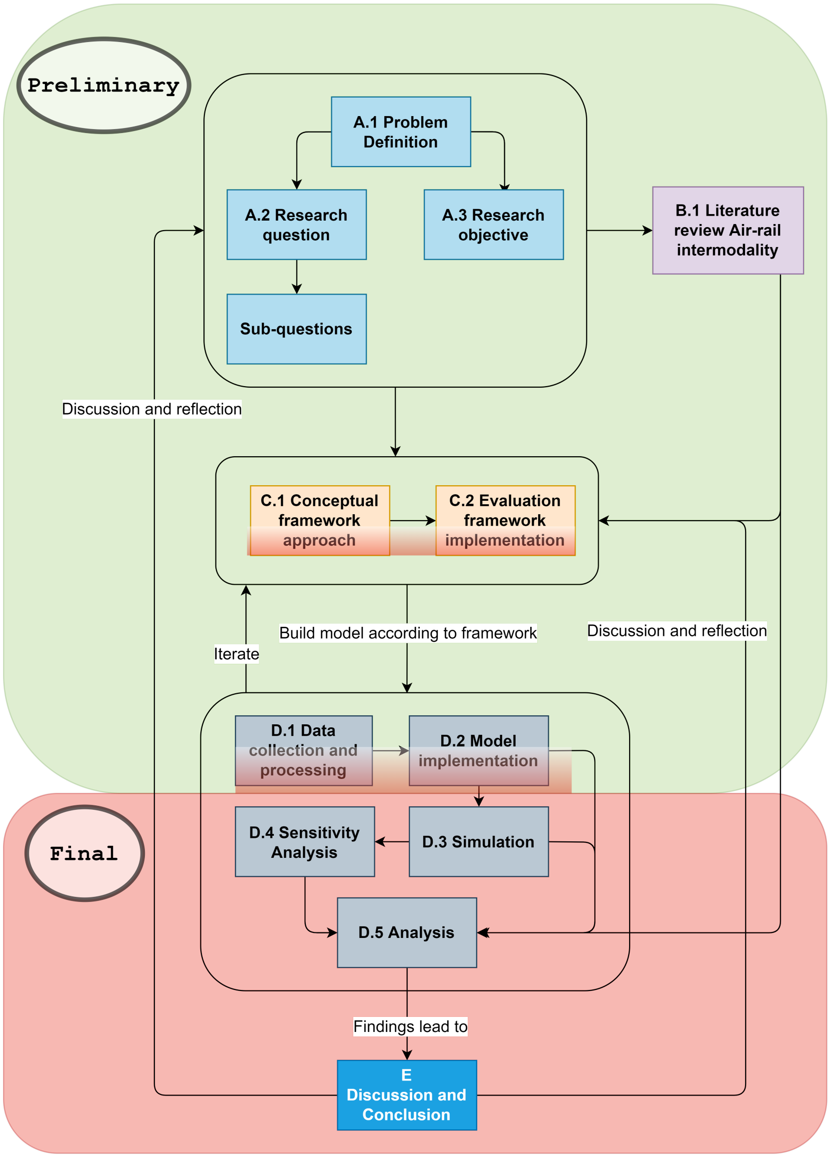
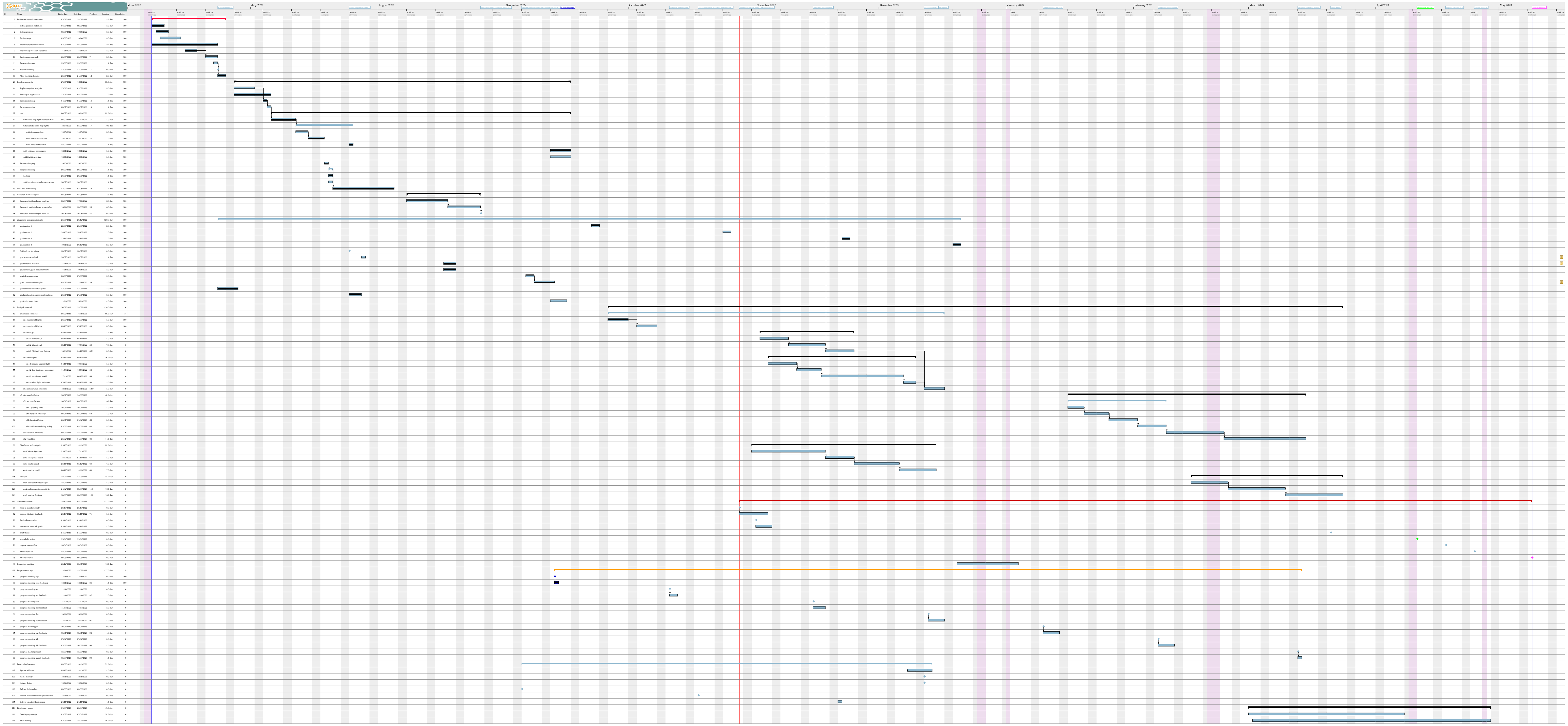


Figure 6.1: Research framework for planning.

Gantt Chart



7 Conclusions

Air-rail intermodal transport implemented for multi-stop flights is a simple but effective way to decrease the number of flights while maintaining a similar total travel time. As air traffic increases and congestion occurs, the benefits of intermodal transportation increase. To enable future passenger growth and connectivity, leaning the air traffic network to utilize the entire transportation network, including ground transportation is a good idea. Airports are integrating rail and becoming intermodal hubs. High-speed rail investments by the EU in the form of railway packages are improving network-level connections. Over the longer-term it is clear that intermodal transportation is key in the European Union's mobility goals.

The literature review concludes that competition and cooperation effects of air with rail both agree that rail reduces congestion by reduction of flights. Also, flights up to 800 km can be replaced without extra travel time. Operational emissions of rail are always better than air, however, life cycle assessments reveal the hidden costs of high-speed rail construction. Many different analytical, data-driven, and empirical methods to estimate ground transportation and air emissions are found which will be adapted to find the carbon emissions in the final report.

The proposed and implemented method covers the entire intermodal integration and is a unique gap in the literature. Reconstructing realistic multi-stop flights is supported by applying logical thinking to passenger and airline decisions. Using real flight data and applying the method per flight allow a granular view of each potential multi-stop flight with time constraints of reaching connecting flights on-time. The passengers taking a multi-stop flight are estimated by applying strategies on transfer windows of incoming and outgoing flights and airport transfer rate data. Ground transportation is integrated using real ground transportation data and merged with the time constraints of the specific flights. The total travel time uses average passenger airport access and egress times from around Europe.

The preliminary analysis provides the affirmation of the ability of rail to substitute short-haul flights amongst some studies in the literature which estimate rail to be the main competitor for air transport between 300 and 800 km. For multi-stop flights distances up to 2000 km are replaceable when replacing both flights. For feeder flights, distances up to 750 km are replaceable while improving the door-to-door travel time. The analysis shows the potential for air-rail intermodal integration and the fact that air travel is not always the black-and-white fastest solution. Passengers should compare travel modes based on the total door-to-door travel time.

Improvements to airline timetables can improve the integration of rail. For instance, early morning flights should be moved to noon time. The discontinuity in international train timetables is suspected to cause a barrier to reach further distances without a large increase in travel time.

Limitations to the study currently are the unknown train capacity to handle extra passengers and the over-estimation of the number of replaceable flights in the analysis due to duplicate flight ids (due to the transfer windows). The algorithm for replacing both flight legs can be improved by choosing better transit times.

The final report shall bring forth the method and results of the direct CO2 emissions compared between air travel and air-rail intermodal transportation. A sensitivity analysis will be made to verify and validate the model. The results from the sensitivity analysis will give a larger insight into the selected parameters and their effect on the outcome. If time allows, the simulation will be conducted, and its analysis will be able to give an estimate of the effects of failed train transfers, and the model's passenger estimated numbers versus reality. Also, a focus on the passengers replaced and flights replaced due to lower than break-even load factor will be analyzed. Some case studies for airports might be fit as well to measure their efficiency and airport pair's intermodal efficiencies.

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