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.

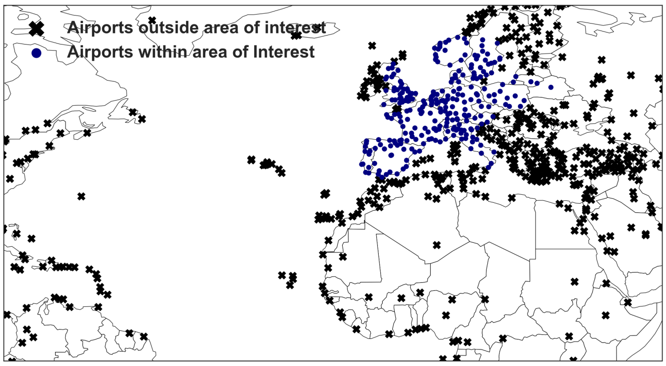


Fig. 1: Airports considered for intermodality within flight data. Map is clipped for clarity.

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 to 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.

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

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

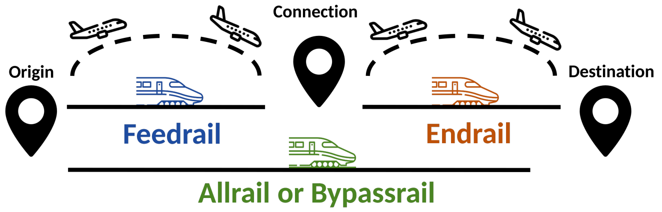


Fig. 2: The intermodal integration categories between the origin, connection, and destination airports: feedrail, endrail, allrail and bypassrail.

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.

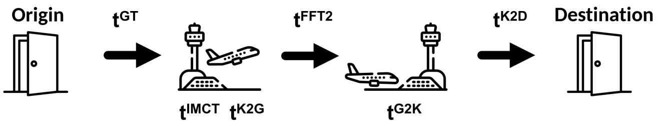
Four different categories were established for the MSFs in order to identify which segments could be replaced. These categories are visually displayed in Figure 2. Feedrail occurs if the first flight leg can be replaced by a 'feeder train'. Similarly, endrail is if the second leg can be replaced. Allrail 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.

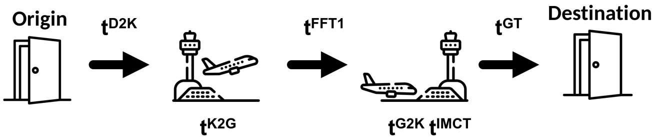
The MSFs were integrated with ground transit to create intermodal journeys. This was done by taking into account the category of MSFs and the average airport access and egress times. For feedrail, ground transit must arrive on time to go from the connecting airport's kerb (entrance) to the gate of the 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.

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].



(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.

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.

$$F_i = \alpha_i \cdot d_{\mathrm{g}}^2 + \beta_i \cdot d_{\mathrm{g}} + \gamma_i \tag{5}$$

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.

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

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

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.

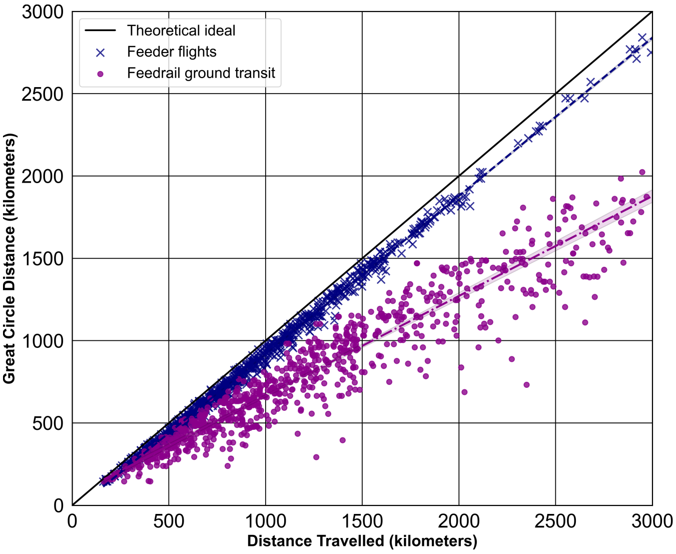


Fig. 4: Theoretical versus actual distance travelled for feeder flights and transit with 95% confidence intervals.

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 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.

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

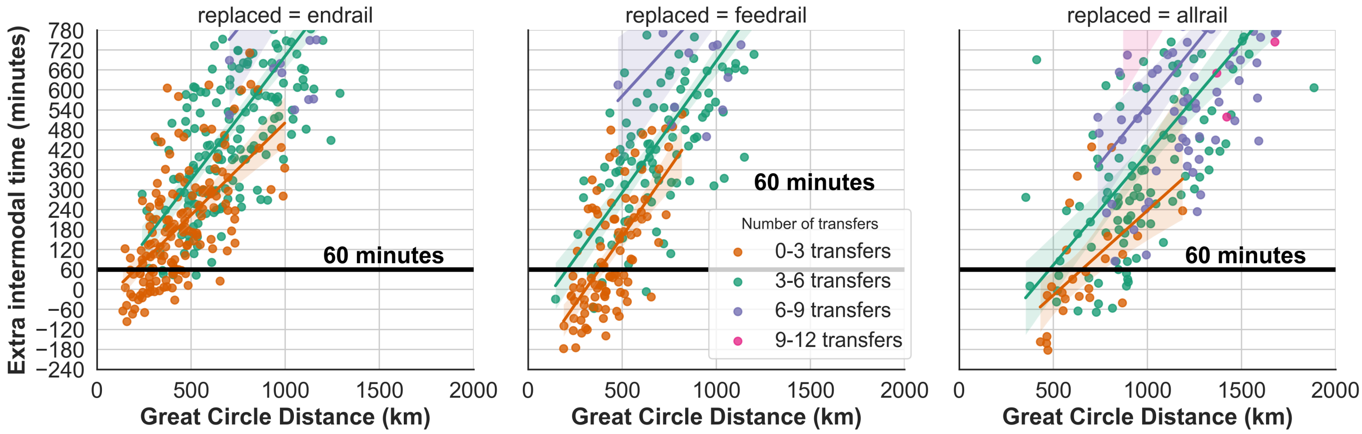
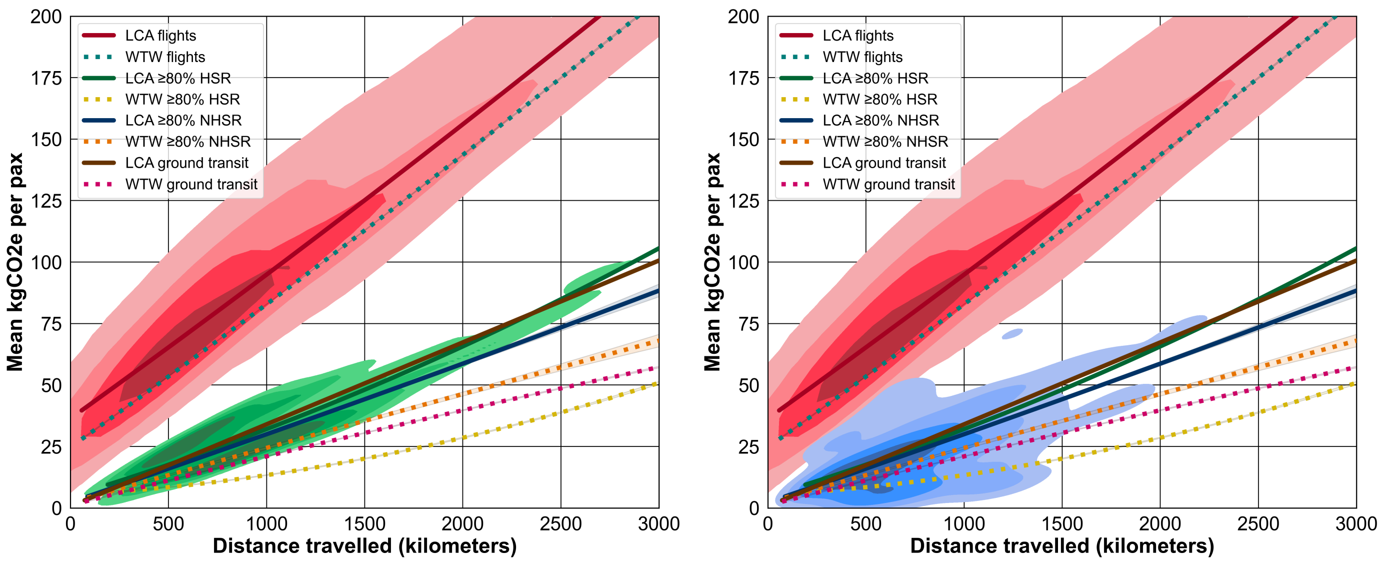


Fig. 5: GCD versus extra intermodal travel time for the top 1000 airport pairs in terms of total transfer passengers.



(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.

growth over distance, while flight emission increases remain linear. This is because the infrastructure costs for flights are 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].

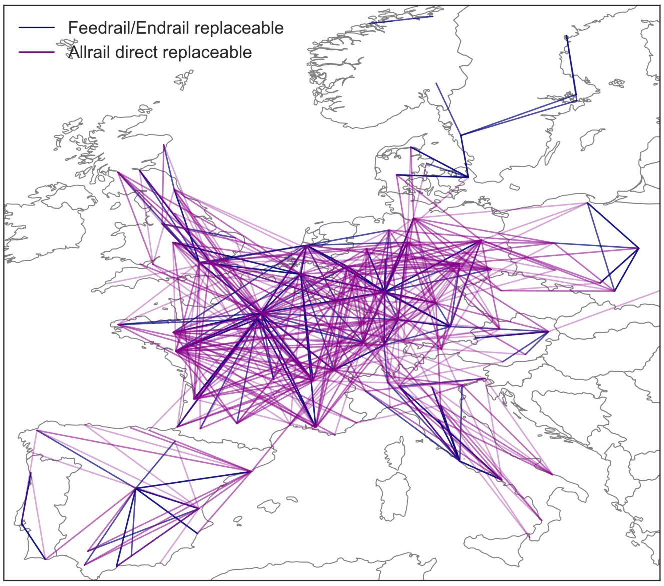


Fig. 7: Replaceable routes for 60 minutes extra travel time. Allrail (intra-European MSFs) is given in direct routes. Only routes with larger than 50% replaceability of MSFs are shown.

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,

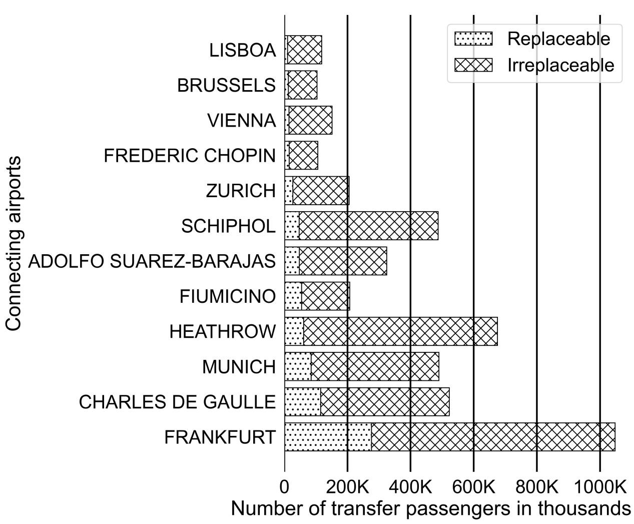


Fig. 8: Replaceable EU transfer passengers at hub airports for a maximum of 60 minutes of extra travel time.

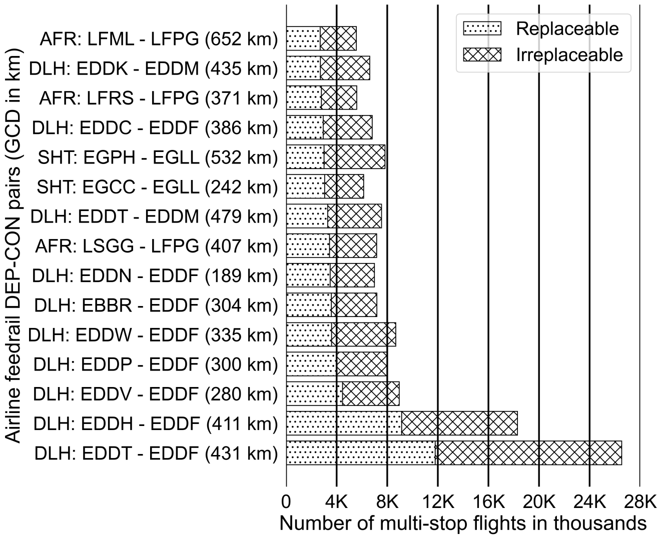


Fig. 9: Top 15 feedrail airline routes in terms of the number of replaceable MSFs for 60 minutes extra travel time.

Frankfurt, Madrid, Zurich, Rome, Warsaw and Munich are intermodally well-connected and are capable to replace many 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 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.

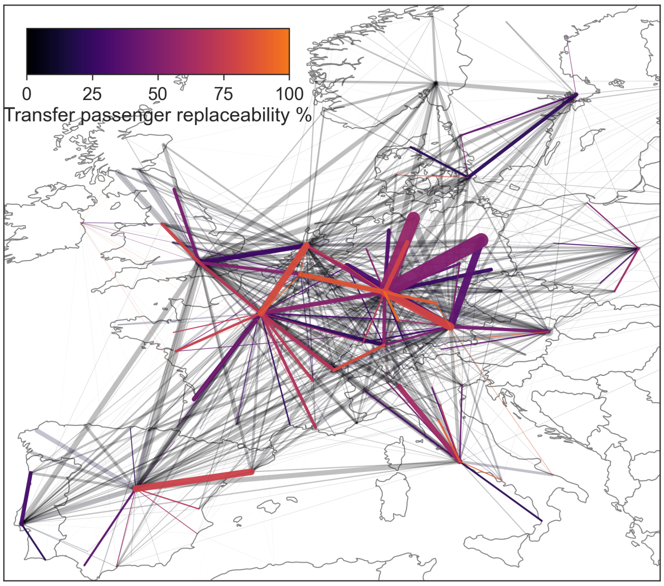
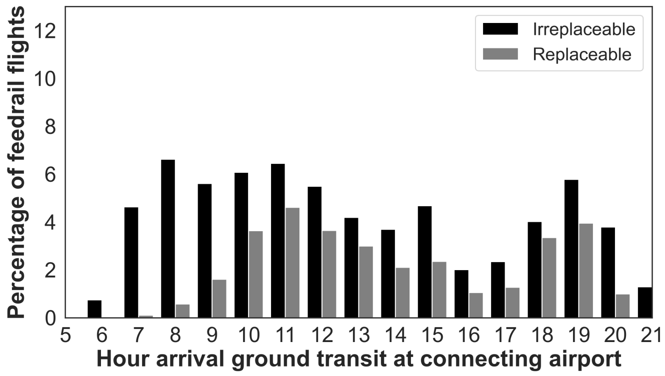
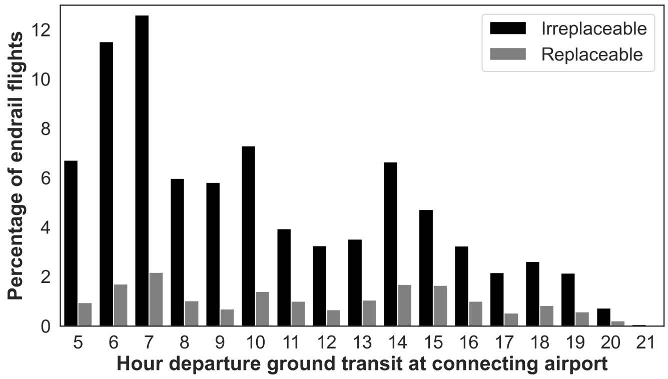


Fig. 10: Replaceable transfer passenger flows for 60 minutes extra travel time. The thickness of the lines represents the ratio to the total number of transfer passengers. Replaceability percentages below 20% are made translucent.

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



(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.

Extra minutes Metrics	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.

region and day, a rule of thumb would be to place feeder flights departing between noon and 9 pm. This corresponds to a 10 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.

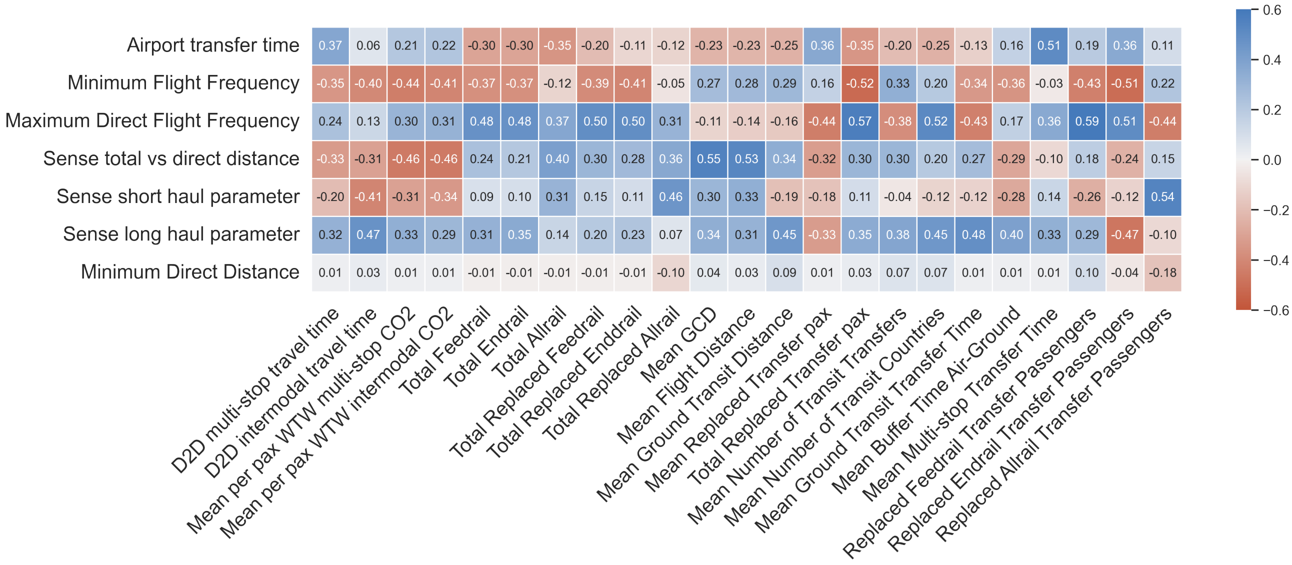
C. Sensitivity of multi-stop flight model

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 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.



	D2D multi-stop travel time	D2D intermodal travel time	Mean per pax WTW multi-stop CO2	Mean per pax WTW intermodal CO2	Total Feedrail	Total Endrail	Total Allrail	Total Replaced Feedrail	Total Replaced Enddrail	Total Replaced Allrail	Mean GCD	Mean Flight Distance	Mean Ground Transit Distance	Mean Replaced Transfer pax	Total Replaced Transfer pax	Mean Number of Transit Transfers	Mean Number of Transit Countries	Mean Ground Transit Transfer Time	Mean Buffer Time Air-Ground	Mean Multi-stop Transfer Time	Replaced Feedrail Transfer Passengers	Replaced Endrail Transfer Passengers	Replaced Allrail Transfer Passengers
Airport transfer time	0.37	0.06	0.21	0.22	-0.30	-0.30	-0.35	-0.20	-0.11	-0.12	-0.23	-0.23	-0.25	0.36	-0.35	-0.20	-0.25	-0.13	0.16	0.51	0.19	0.36	0.11
Minimum Flight Frequency	-0.35	-0.40	-0.44	-0.41	-0.37	-0.37	-0.12	-0.39	-0.41	-0.05	0.27	0.28	0.29	0.16	-0.52	0.33	0.20	-0.34	-0.36	-0.03	-0.43	-0.51	0.22
Maximum Direct Flight Frequency	0.24	0.13	0.30	0.31	0.48	0.48	0.37	0.50	0.50	0.31	-0.11	-0.14	-0.16	-0.44	0.57	-0.38	0.52	-0.43	0.17	0.36	0.59	0.51	-0.44
Sense total vs direct distance	-0.33	-0.31	-0.46	-0.46	0.24	0.21	0.40	0.30	0.28	0.36	0.55	0.53	0.34	-0.32	0.30	0.30	0.20	0.27	-0.29	-0.10	0.18	-0.24	0.15
Sense short haul parameter	-0.20	-0.41	-0.31	-0.34	0.09	0.10	0.31	0.15	0.11	0.46	0.30	0.33	-0.19	-0.18	0.11	-0.04	-0.12	-0.12	-0.28	0.14	-0.26	-0.12	0.54
Sense long haul parameter	0.32	0.47	0.33	0.29	0.31	0.35	0.14	0.20	0.23	0.07	0.34	0.31	0.45	-0.33	0.35	0.38	0.45	0.48	0.40	0.33	0.29	-0.47	-0.10
Minimum Direct Distance	0.01	0.03	0.01	0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.10	0.04	0.03	0.09	0.01	0.03	0.07	0.07	0.01	0.01	0.01	0.10	-0.04	-0.18

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.

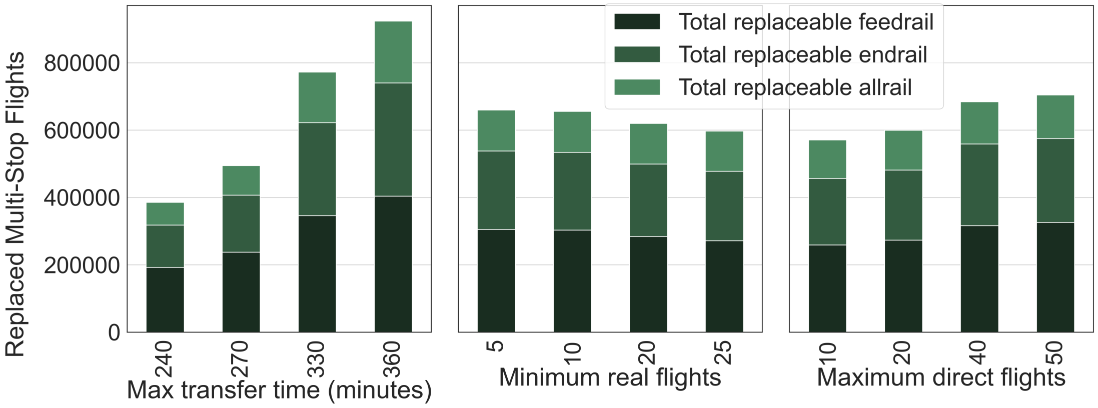


Fig. 13: Output sensitivity of the replaced MSFs depending on the input parameters.

The other input parameters given in Table I have a small effect. The maximum direct flight frequency and maximum transfer 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.

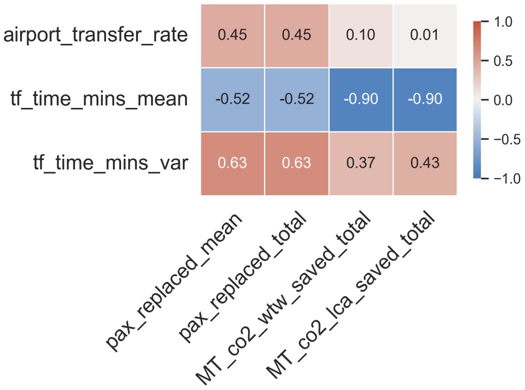


Fig. 14: Correlation matrix of the simulation using the Spearman method, highlighting the influence of the airport transfer rate and transfer distribution parameters on the passenger numbers and emissions.

To bypass this limitation, future work can merge journey data from other providers such as Interrail [41], with permission.

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. 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.

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.

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.

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].

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.

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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