Analysing the feasibility of an alternative modality for short-range air transport

An Open Approach

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An Open Approach

Thesis report

by

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Preface

This thesis report is the culmination of the last five years that I spent in Delft studying Aerospace Engineering.

First and foremost, I would like to thank my family: my father, mother and brother, for all their support during my studies. They have always been a cornerstone through thick and thin and are a constant source of motivation for me.

I would also like to thank my supervisors Junzi Sun, Alessandro Bombelli and Jacco Hoekstra for their insightful discussions and constructive feedback throughout this project.

Last, but not least, I would like to thank all the friends I made and the peers I worked with, for making my time here in Delft amazing and worthwhile. In particular, I would like to extend my heartfelt gratitude to the study association VSV 'Leonardo da Vinci' and the Online Learning Team, where I had many great experiences over the years.

Bryan Quadras
Delft, June 2024

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Contents

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Nomenclature

Abbreviation	Definition
AAT	Actual Arrival Time
AOBT	Actual Off-Block Time
CO_2	Carbon Dioxide
EU	European Union
FAT	Filed Arrival Time
GHG	Greenhouse Gases
GPL	GNU General Public License
GTFS	General Transit Feed Specification
HSR	High Speed Rail
IATA	International Air Transport Association
ISA	International Standard Atmosphere
LoS	Level of Service
MWE	Minimum Working Example
SESAR	Single European Sky ATM Research
WGS84	World Geodetic System 1984

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Scientific Article

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Analysing the feasibility of an alternative modality for short-range air transport

Bryan Quadras
Supervisors: Junzi Sun, Alessandro Bombelli, Jacco Hoekstra

Abstract

The advent and rise of low-cost, high-frequency short-haul flights in Europe increasingly necessitates the need of more sustainable travel methods for trips with a distance under 1000 km. Many different proposals and policies have been put in place, including full flight bans for trips under 500 km, but the research space still has not embraced a possible co-existence of major air and ground transport options in this segment. This research addresses this by developing a reproducible method using openly accessible data to assess air and rail network capacities of three of the busiest air transport routes in Europe. A capacity analysis is conducted and the modelling of travel time, travel cost, change in carbon dioxide emissions and passenger experience is performed, in order to investigate the feasibility and logistics of shifting passengers between air and rail. The study finds that 30-50% of passengers could shift completely to trains, given sufficient rail network capacity, significantly reducing total carbon dioxide emissions and improving passenger experience throughout.

I. Introduction

In recent years, the European Commission meeting in line with the objectives of the European Green Deal, has started work on increasing connectivity between rail networks and promoting more sustainable travel through its aim of placing a stronger focus on sustainable urban mobility. However, there are currently very dense air networks of low-cost, high-frequency short-haul flights between many cities in Europe [1]. While air transport provides passengers with convenient transportation options due to its high operational density, it is crucial to emphasise that aviation still contributes very significantly to transportation emissions. Research indicates that short-haul air transport specifically emits a considerably higher amount of greenhouse gases (GHG) per passenger kilometre travelled compared to most ground transportation methods [2].

The effects of air-rail competition and cooperation have been studied extensively, generally in respect to inter-modal trips with a combination of an air segment and rail segment. Most studies conclude that inter-modal trips bring about benefits to travellers and help with the reduction of environmental impact. However, there is not much research focused on the logistics of shifting passengers from one segment to the other. Furthermore, any studies on capacity analysis are generally limited to the specific region at play.

The objective of the research presented in this paper is to develop a reproducible approach to accurately determine the capacity of air and ground transport networks in key regions of interest, capture factors such as total travel time and passenger experience in a model, and use key indicators and results from this model to better investigate the feasibility and logistics of shifting passengers from short-haul flights to ground transport options for a given trip and direction between two cities. The results from this research will help air transport and ground transport providers gauge how much capacity the current infrastructure can handle and help legislators adjust their policies on short-haul transport to better meet the goals set out in the European Green Deal.

Another objective from the get-go is for this research to be based on open principles as much as possible. To the best of the authors' ability, all data and code is made accessible to help the research space further develop and allow any research presented to be verified.

This research is split into three distinct parts. First, the procedure to obtain the data used and process it for further analysis will be presented. Next, the full approach to analysing the capacity of both air transport and ground transport options for a given city pair will be discussed. The feasibility of shifting passengers and the extent to which it is possible will be included in this discussion. Finally, for several carefully selected city-pairs, a simple model will be developed and used to ascertain and monitor key parameters and indicators such as total waiting time, passenger experience and cost for different situations and scenarios involving trips between those cities.

Section II will go over a brief discussion on the current State of the Art with respect to the research space. Section III will detail the methodology behind the three aforementioned parts of the research. The main assumptions of the research will also be discussed. In Section IV, the results will be presented for every stage of the research. Between each subsection, a discussion will be present going over the meaning of the results of that stage and the implications for the overall results of the research. The results of a sensitivity analysis are also presented. Finally, Section V will present an conclusion to the research and present a outlook of its implications in the research space. Recommendations for follow up research will also be discussed.

II. State of the Art

For this research, a brief investigation into the current state of the art in several fields was conducted. This was crucial in the early parts of the research as it allowed the author to identify what had already been researched in different fields and appropriately tune and inform the aims and goals of this research.

A. Air and ground transport data for research

Obtaining data for research purposes has been a very tricky endeavour in the past few decades. However, the recent rise of public transport data provided through the GTFS format has made research, such as this study, possible.

As such, several studies and previous theses ([3, 4, 5, 6]) show that data obtained from OpenSky or EUROCONTROL for air transport, and GTFS or open schedule data published by ground transport providers can be used reliably for capacity analysis.

Data relating to price or demand and supply of flight or train tickets is much less reliable. Studies delving into these topics generally only have the option to investigate the spending capacity of customers rather than raw data from airlines or ground transport providers [7].

B. Effect of short-haul flight bans on mobility

A study [8] by Cantos-Sánchez investigated the efficacy of short-haul flight bans on reducing ”environmental external costs”. The main result was that this depended heavily on a case-by-case basis, and that external costs were not always reduced. However, it was clear that a modal shift was provoked on such a ban.

With the effects being hard to model in the framework of this study, the choice is made to focus instead more on a co-existence of flight and rail and investigate the effects of shifting passengers from the former to the latter.

C. Capacity analysis of transport networks

Analysing the capacity of transport networks is a crucial step in determining the feasibility of shifting passengers and understanding the underlying factors that affect it.

Since July 2023, the EU SESAR 3 Joint Undertaking partnership has launched an initiative called MultiModX (Integrated Passenger-Centric Planning of Multimodal Transport Networks) whose goal is to deliver a set of innovative multi-modal solutions and decision support tools for the coordinated planning and management of multi-modal transport networks [9]. MultiModX has fostered a lot of research in the space of multi-modal transport networks. Delgado et.al. [3] have also looked into modelling the integration between some air and rail networks and evaluating its effects.

While the main aim of this study is focused on the co-existence of air and rail, these studies will still be useful.

D. Measuring passenger experience

Passenger experience is generally thought about as being a qualitative factor and not necessarily something which can be directly quantified. Nevertheless, there have been several studies and approaches to measuring passenger experience in different transport networks, across complete journeys.

Notably, the METPEX (A MEasurement Tool to determine the quality of the Passenger EXperience) project [10] has published various papers [11, 12, 13] that go over the key factors that help to determine and quantify passenger experience in door-to-door journeys. In addition, factors such as user satisfaction and average waiting times at airports, rail stations and bus stations, can also contribute towards or detract from passenger experience.

E. Effects of air and ground transport inter-modality

Air and ground transport inter-modality effects including with respect to competition and cooperation between air and rail transport networks have been a subject of many studies in the past half-decade.

An important aspect of competition between air and rail transport is with the possible impact of HSR (High Speed Rail) based travel on flight frequency and demand. Jiang [14] found that introducing a low-cost HSR option to the Paris to Marseilles route reduced air traffic in the same route by 33%.

With respect to cooperation, Chiambaretto [15] found that over the past few years inter-modality agreements have brought upon significant benefits, including the stimulation of shifts from air to rail transport in many cases.

III. Methodology

A. Obtaining and processing data

The availability and ease of access to data for research purposes is very crucial and usually a significant hurdle before processing and analysis can begin. As detailed in the State of the Art, in the last 5-10 years, ground transport providers have begun to publish their data and make it available open-access for research purposes. However, data from air transport and air traffic control providers, albeit available for research purposes and used in this research, is still not published as open-access.

1. Air transport data

The flight data used in this research is obtained from EUROCONTROL. The choice was made to make use of flight data specifically from March 2019, and not from more recent data. This was done to mitigate the effect that the COVID-19 pandemic had on air traffic from the start of 2020 [16]. This dataset primarily consists of flight data where the planned departure date was in March 2019. An overview of the relevant parameters that will be used for processing can be seen in Table 1.

Table 1: Relevant parameters of ECTL Research Flight Data used (adapted from [17])

Parameter	Description
ECTL_ID	A unique numeric identifier for each flight in the dataset
ADEP	ICAO airport code of departure airport of the flight
ADES	ICAO airport code of destination airport of the flight
Filed Arrival Time (FAT)	Time of arrival (in UTC) based on last filed flight plan
Actual Off-Block Time (AOBT)	The time that aircraft departs from its parking position.
Actual Arrival Time (AAT)	Time of arrival (in UTC) based on ATFM-updated flight plan
AC Type	ICAO aircraft type code
Actual Distance Flown [nm]	Distance flown in nautical miles

The first step in the data processing stage was to aggregate the number of flights that have departed from a certain airport after grouping the data by the origin airport field (ADEP). The intention is to filter out the flights by choosing the top 100 airports with the largest number of flights that departed the airport.

Then, more data about the top 100 airports was obtained [18]. This includes details such as the place and city that the airport is located in, whether the airport is classified as being large, medium or small, and the coordinates of the principal terminal location.

Once the airport information dataset was ready, the flight dataset was grouped by origin and destination airport pairs, and for every pair the mean distance, mean duration, total flight count and most common aircraft typecode were determined. The total flight count was divided by the number of days in March 2019, to arrive at a figure for a number of daily flights for a given origin and destination airport pair.

Lastly, using the city field from the aforementioned airport dataset, a final dataset was prepared with aggregated data for every city pair combination. Airports that had a connection were kept, while airports with no connections found were discarded. This resulted in a record for every unique combination of airport pairs with the correct classification of the associated city and country alongside. The data is now in a state where it can be used further for capacity analysis. Figure 1 shows a flowchart of the data processing workflow.

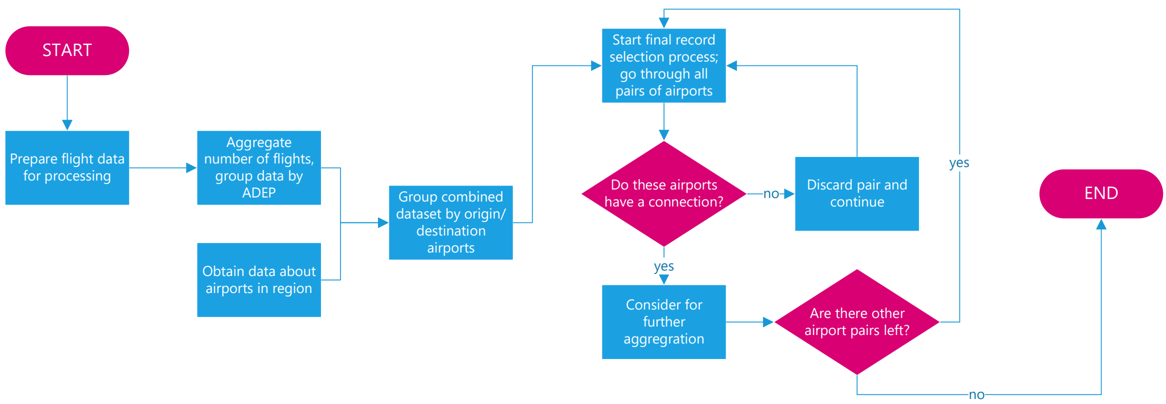


Figure 1: Flowchart of data processing workflow for flight data

2. Ground transport data

Data for ground transport services is more accessible in comparison to air transport data due to widespread adoption of the General Transit Feed Specification (GTFS) standard by ground transport providers. In the early 2000s, most transport providers in Europe only released data about their services to companies in a closed manner. However, since the release of GTFS by Google in 2006, most providers now provide up-to-date data feeds about their services in the format. This has not only helped popular services such as Google Maps from delivering accurate travel plans with trains and buses to their customers, but also resulted in a boost of mobile and desktop software applications that could make use of transit information for different purposes. Most importantly, with providers deciding to make their data feeds openly accessible, it has the consequence that using that data for research is predictable as the GTFS format is an open standard (CC BY 3.0) and thus an approach built to analyse one provider's transit data can easily be adapted to work with updated data or data from another provider, without much work.

There are two types of GTFS feeds, GTFS Schedule and GTFS Realtime. For this research, only the former will be used, as the latter contains realtime data such as current vehicle positions and in the moment delay information which is not useful or appropriate for the aims of this research. The GTFS Schedule specification states that in every dataset there are specific files that must be present as they are required to get a minimum working example (MWE) using the data [19].

Table 2 shows the different files that are present at a minimum in a data feed. Every file represents a table with rows of records. The specification also details which fields must be provided for every record in every file.

Table 2: Files that make a part of a GTFS Schedule data feed (adapted from [19])

File Name	Presence	Description
agency.txt	**Required**	Transit agencies with service represented in this dataset.
stops.txt	**Required**	Stops where vehicles pick up or drop off riders. Also defines stations and station entrances.
routes.txt	**Required**	Transit routes. A route is a group of trips that are displayed to riders as a single service.
trips.txt	**Required**	Trips for each route. A trip is a sequence of two or more stops that occur during a specific time period.
stop_times.txt	**Required**	Times that a vehicle arrives at and departs from stops for each trip.
calendar.txt	**Conditionally Required**	Service dates specified using a weekly schedule with start and end dates. Required unless calendar_dates.txt contains all dates of service.
calendar_dates.txt	**Conditionally Required**	Exceptions for the services defined in calendar.txt. Required if calendar.txt is not present.

For this research, data was obtained for the countries of Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Spain, Spain and United Kingdom. The train data for the United Kingdom is still only issued as a file with the TransXChange format. In order to also make use of it for this research, the tool UK2GTFS [20] (licensed under GPL-3) was used in order to convert the files into a familiar GTFS data feed.

Once all the GTFS feeds were prepared, processing could begin. Since every feed must contain the same files according to the specification, an approach could be applied generally to all countries' data feeds.

The main approach to processing the data was to first merge the relevant files under each data feed, such that for every data feed, a full table representation can be used with the relevant columns retained in the table.

Specifically the files `stop_times.txt`, `stops.txt`, `trips.txt` and `routes.txt` were merged using the `trip_id` identifier. Every record in the merged table represents a stop of a service on a trip (for instance, the stop at Delft Station on the service from Amsterdam Centraal to Rotterdam Centraal). The resultant merged table contains the columns of route_id, trip_id, stop_id (all unique identifiers in their own respective files), the sequence of the stop in the service, an arrival time and departure time at that specific stop and the latitude and longitude of the stop.

When looking at the de facto standard of the content and structure used by transport providers in the GTFS feeds they provide, a clear pattern emerges. Most providers have specific service schedules running only on certain days throughout the week. Other providers have regular and special schedules that run specifically on a range of dates (such as from 02 May 2024 to 26 May 2024). This variation and the duplication of data in the GTFS feeds led to the decision to filter the GTFS routes in such a way that only the services with the least exceptions or most additions were taken forward for further processing. In this way, only the services that run for the longest throughout the year (or time frame represented in the data feed) were taken into account, as they would be most representative for capacity analysis and the transport model.

Once the filtered GTFS route records were obtained for every data feed processed, they were combined into one large table and saved at this stage. The next stage is the further processing of all these records. For all the records in the table, the latitude and longitude are converted to X, Y coordinates using a projection based on the WGS84 geodetic system. Given that the maximum scope of countries considered are within the continent of Europe, it was decided that the projection would be sufficiently accurate for this research.

Another important step at this stage of processing is merging stops that are very close to each other. Specifically, stops within 1 km of each other were merged by assigning a new unified identifier and a unified stop name. This process was done for all stops in the table, even those that did not need merging, in order to keep the records consistent. The main reason why merging stops close to each other is necessary is because in rare cases where GTFS data feeds contain duplicate stops (due to stops being close to the border of two countries), merging stops would streamline the combined table and remove situations where a route cannot be found because of a difference in stop name. In other situations, the same stop may be represented twice for each direction of service. Also in this situation, merging prevents misguided routing artefacts later on in analysis.

Once the GTFS route records have been streamlined, a graph representation of the records is created. In any graph representation of the records, a node represents a station where services and vehicles start and stop. An edge then represents a connection between two stations with information on both the departure and arrival stations. A graph representation is used to easily route and compute total distance and duration between two stops in the combined processed dataset.

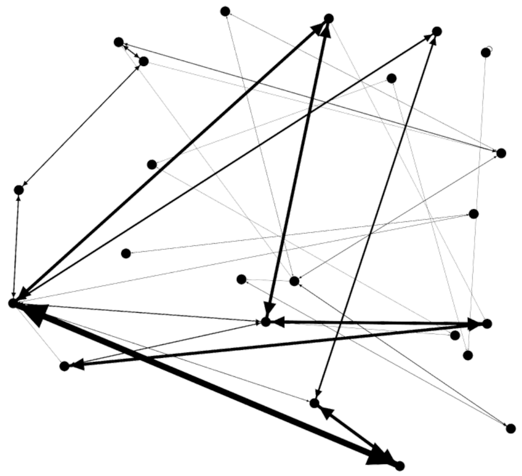


Figure 2: The directed multigraph representing nodes and edges for the Eurostar data feed (own work)

To best represent train stations and connections in a graph, the choice of using a Directed Multigraph was made. Using a multigraph was necessary as stations can contain multiple edges (or services) or a loop with the same station is possible (for instance in train services which operate on a circular line). Figure 2 shows a representation of the directed multigraph for the Eurostar provider data feed. Obtaining edges from the table representation that is currently present is trivial as on a given service, all stops have a field *stop_index* that increases in ascending order. An important distinction to be made is that stop indices need not be consecutive [19]. Although it is counter intuitive not to use consecutive stop indices, some providers only provide data with non consecutive indices, therefore care was taken to order stops correctly in all cases.

The last step in processing the train data is the most computationally intensive step. At this stage a graph with the set of all nodes and edges is present, but on its own the graph cannot be used to compare against flight data for a capacity analysis or further modelling. Therefore, the graph and the extensive set of city pairs that were already represented in the flight data will be used in order to compile a final table. This table will contain the shortest duration and distance to travel on the train between the city pairs. The results from both the flight and train data will be an instrumental prerequisite to the selection of city pairs for further research.

For the final processing stage, a carefully prepared set of steps are applied. For every city pair present in the flight data, the closest train stations to the city's centre are found. This is done programmatically using a k-d tree structure of all stations x and y coordinates. This tree representation is used to quickly run a nearest neighbour search with the city centre coordinates as the query. A k-d tree is used over other representations because of its performance and high efficiency when querying for neighbours in a 2-D structure around a given point compared to octrees.

Once the unified identifiers of the closest stations have been found, a shortest path function is applied to find the shortest possible route between the stations (and hence between the two cities). A modified

Dijkstra algorithm is used for this. Modifications are made in order to ensure that the route does not contain segments of trains with a lot of time delay (waiting time) between them. Adding a time penalty clause to the Dijkstra algorithm helps to ensure that this condition is met. Algorithm 1 describes the pseudocode of the modified Dijkstra algorithm.

Algorithm 1 Pseudocode of modified Dijkstra algorithm used for shortest path determination

$dist \leftarrow$ {node: inf for node in G}
$dist \leftarrow$ {node: {"node" : None, "key" : None, "data" : None} for node in G}
$last\_trip\_id \leftarrow$ { node: None for node in G}
$dist[orig] \leftarrow$ start_time
$transfer\_penalty \leftarrow 10$
$time\_penalty\_factor \leftarrow 0.1$
$pq \leftarrow [(start\_time, orig)]$
$visited \leftarrow set()$
while pq **do**
    $current\_time, current\_node \leftarrow pq.pop()$
    if $current\_node$ in $visited$ **then continue**
    else $visited.add(current\_node)$
    end if
    $arrival\_time\_current \leftarrow start\_time$ if $current\_node = orig$ else $current\_time$
    for `neighbours in edges of current node` **do**
        if `arrival time is after departure` **then continue**
        end if
        $time\_penalty \leftarrow time\_difference * time\_penalty\_factor$
        if `trip_id remains the same` **then** $penalty \leftarrow 0$
        else $penalty \leftarrow transfer\_penalty$
        end if
        $score \leftarrow current\_time + duration + penalty + time\_penalty$
        if $score <$ `last closest neighbour score` **then**
            `last closest neighbour score` $\leftarrow score$
            `last closest neighbour` $\leftarrow \{node : \{"node" : current\_node, "key" : key, "data" : data\}$
            $pq.push(score, neighbour)$
        end if
    end for
end while

The output of the shortest path function can have two possible results. The first is that a route was found between the cities which is guaranteed to be the shortest within the graph. The other possibility is that no route could be found between the cities with the strict conditions set in the modified Dijkstra algorithm, in which case the city pair is not considered any further. If the shortest route is indeed found for city pair, this is saved in a final table of results for the train data, and the total distance and duration are calculated by traversing the edges that make up the shortest route returned by the function. Subsequently, the same process as mentioned is run for the next city pair until all city pairs have been iterated through.

Table 3 shows a sample of records from the final results of the processing of the train data and Figure 3 shows a flowchart of the data processing workflow for train data.

At this stage, the processing of the train data is complete. The main outputs are the graph with the nodes and edges of GTFS routes from the aforementioned countries' data feeds, and a final table with data on shortest distance and duration between all city pairs also considered during the flight data processing steps. Before both of these outputs can be taken forward to the city pair selection stage, considerations must be made on the performance aspects of using a large graph for analysis only in certain regions and between certain city pairs.

It should be noted that the complete graph has about 4800 nodes and *10 million* edges. Two concerns were the size of the complete graph and computational resources required to work with this for further research. The disk space occupied by the complete graph was about 3.5GiB and in practice, at least 8GiB of RAM was needed to use this graph actively in a Python-based environment. While these requirements are not very high at the time of writing for computational resources and research purposes, there were noticeable

Table 3: Sample of records from final table of processed Train Data (own work)

no.	city_origin	city_destination	duration (mins)	distance (km)
275	Zürich	Nantes	530.0	1188.68
557	Cologne	Hamburg	225.0	381.96
947	Luxembourg City	Hanover	389.0	648.77
179	Munich	Bristol	614.0	1176.94
57	Amsterdam	Budapest	858.0	1196.4
818	Venice	Frankfurt	603.0	753.01
1198	Charleroi	Luxembourg City	102.0	117.22
1143	Belfast	London	616.0	523.07
925	Luxembourg City	Berlin	463.0	800.11
410	Geneva	Bordeaux	369.0	1000.97
1154	Aberdeen	London	383.0	693.66
995	Bristol	London	80.0	165.43
778	Marseille	Amsterdam	437.0	1116.51

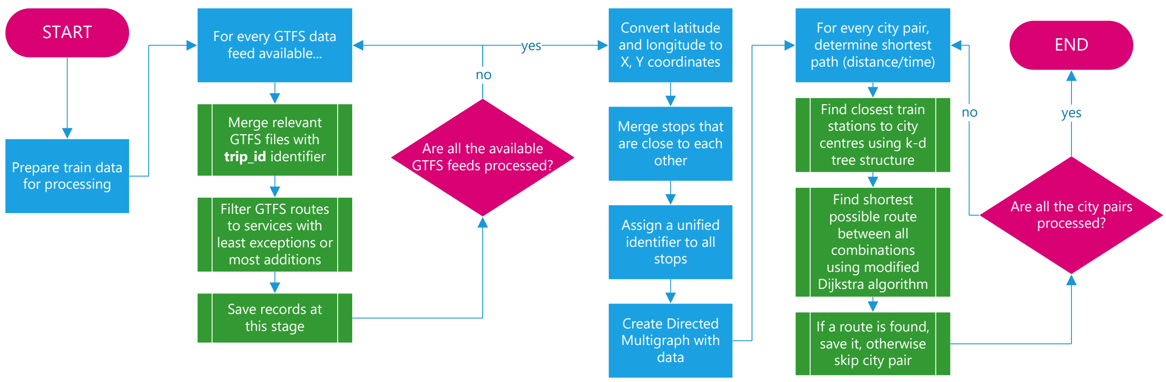


Figure 3: Flowchart of data processing workflow for train data

delays when trying to load and work with the graph. To mitigate these issues, the author decided to make use of subgraphs.

Subgraphs, in this context, are graphs in the identical format as the complete graph, with the exception of only containing data from one or two data feeds, depending on the region being analysed. Using subgraphs in the further research instead of the complete graph resulted in a very noticeable computational speed improvement, and much less resource usage.

B. Selection of city pairs

In the framework of this research, the aim is to investigate travel between several city pairs through a capacity analysis and deeper look at the multi-modal transport situation. To facilitate this aim and respect the constraints and limited resources of this project, a decision was made to choose three city pairs using specific criteria, for the capacity analysis and further modelling and simulations. When choosing the pairs, care has been taken to choose city pairs for which results are likely to count significantly towards understanding the feasibility, logistics and large scale effects of shifting passengers. At the same time, for the city pairs chosen, it should be relatively trivial to obtain open data that is accurate enough for an impactful capacity analysis result.

With these requirements in mind, it was natural to choose city pairs with a large amount of air traffic every day (number of flights per day) between them, while ensuring that the city pairs chosen were in distinct regions of interest such as to be able to gauge if there are differences in feasibility with different regions.

Table 4: Top twenty unidirectional city pairs ranked by descending number of daily flights

Rank	Origin city	Destination city	Daily flights	Rank	Origin city	Destination city	Daily flights
1	**Amsterdam**	**London**	**54**	11	Nice	Paris	27
2	**London**	**Amsterdam**	**53**	12	London	Frankfurt	27
3	London	Edinburgh	43	13	Frankfurt	London	26
4	London	Geneva	43	14	London	Paris	25
5	Edinburgh	London	43	**15**	**Berlin**	**Frankfurt**	**25**
6	Geneva	London	43	**16**	**Frankfurt**	**Berlin**	**25**
7	**Paris**	**Toulouse**	**34**	17	Barcelona	Madrid	25
8	**Toulouse**	**Paris**	**33**	18	Munich	Berlin	25
9	Barcelona	London	31	19	Paris	London	25
10	Paris	Nice	28	20	Berlin	Munich	24

Table 4 shows the top twenty (unidirectional) city pairs, ranked in descending number of daily flights, with a matching train route also present in the final table for train data. The rows, highlighted in green, designate the three chosen city pairs (bidirectional) which are: **London — Amsterdam**, **Paris — Toulouse**, and **Berlin — Frankfurt**.

The motivation behind choosing these three are as follows. For Amsterdam — London, the main motivation was that it has the highest number of daily flights in the region with around 107 flights every day in total in both directions. The very large number of flights is interesting for the upcoming capacity analysis, as it will be crucial to see how many passengers from these flights could possibly be shifted to trains and whether the possibility rises of reducing the number of flights in any capacity. In addition, the effects of Brexit in terms of border control could result in disproportionate passenger experience during upcoming modelling.

For Paris — Toulouse and Berlin — Frankfurt, a similar motivation was present even though their number of daily flights was markedly less than Amsterdam — London. They were specifically chosen over the other pairs present in Table 4 because they were the next city pairs which were in distinct regions and did not involve London as an origin or destination city. This is important in order to see the effects that region could make on further research.

C. Capacity analysis

With the data processed and city pairs selects, the methodology behind the capacity analysis can now be explored. In the spirit of ensuring that this analysis and all steps reported thus far can be reproduced, an approach with minimal input variables is used. For every city pair, both directions are investigated to see if there are any disproportionate effects in a certain direction.

In the framework of this analysis, capacity is measured for the number of passengers per day. This way, all the data tables obtained thus far can be used directly. The first step in the capacity analysis is to look at determining capacity of all flights in the chosen direction. From the processed data, the most common typecode of flights between all airports of the city pair and the number of daily flights, are used to get a figure for the number of passengers likely to travel on that day. The assumption is made that the flight will be in a 'high' configuration (about 70%-80% of maximum capacity). Data for the maximum capacity for most flight types were obtained from data made available on the OpenAP repository [21].

For train capacity, more information is required about the exact stops used throughout a train trip. For this, a different approach is followed. We first load in the relevant subgraphs for the city pair for which the procedure is being followed and obtain the closest unified stop for both the origin and destination cities. Then, the shortest path algorithm is applied so that the exact edges of the train trip are obtained. In addition to the edges, information about the type and number of carriages in every train service is obtained from public sources. The GTFS data feeds corresponding to the subgraphs are also queried to get the unique number of departures for the whole trip every day. Lastly, every edge is traversed to find the maximum number of passengers that can travel through all steps. The data about the maximum capacity per every segment/edge must also be defined for this procedure to be successful.

Once figures for passengers per day by flight and train are obtained, the feasibility of shifting passengers is tested. For this, it is assumed that passengers will be shifted from the flights to the trains. The utilisation rate of the train is an important factor which is taken into account here. Values from about 50% to 80% will be levied for utilisation rate to see its effect on the maximum percentage of passengers on flights that can be shifted to trains. The main limitation of this capacity analysis is the accuracy of all figures and data used. However, even with assumptions and reasonable figures used, looking at percentage of passenger shift possible vs utilisation rate will be useful to gauge the feasibility of shifting passengers as a first step before any further simulations.

D. Multi-modal transport model

After the capacity analysis, it is important to investigate the far-reaching effects behind the logistics of actually shifting passengers from flights to trains. The goal is to develop a model that takes as input percentage shift passengers for a given city pair, and outputs indicators such as change in total carbon dioxide emissions per passenger, change in passenger experience, and change in the number of flights and trains utilised after the shift.

Passenger experience is a very subjective metric and it is not directly clear how one would measure this, let alone access any data from providers who may have indications on user satisfaction. To sufficiently represent passenger experience, a factor that can often make or break a full journey is used: total travel time. Total travel time includes all waiting time alongside the travel time of the flight or train trip. It was much easier and reasonable to obtain and estimate to a high degree how long every component of a trip either by flight or train would cost in time.

For flight timings, the Level of Service concept set forward by IATA for airport terminal planning in Figure 13 is used. These guidelines give a good starting base for determining the different time components that form part of the total travel time. All time components considered for the flight and train trips for every city pair are described in Table 5. It is important to note that regional border effects are also taken into account in waiting time determination, such as the time taken for passport control checks for a trip between Amsterdam and London.

Table 5: Time components that make up the total waiting time

Component	Description / full form	Implies
ADT	Time to arrive to terminal	Time to arrive to airport or train station
TTD	Total time to departure gate	Time taken for check-in / ticket check, passport control, security and boarding
TTO	Total time before take off	Waiting time until plane ready to take off or train ready to leave station
TAL	Total time after landing until end of taxiing	Waiting time until possible to leave aircraft or train
TTA	Total time until exit of terminal	Time for passport control, possible bag-pickup and customs
FIN	Time to arrive to final destination	Time to arrive to destination city centre region

For the determination of several of the time components, a lower and upper bound are considered. These can best be described as the best and worst case for how much time that part of the trip may take. The main assumptions made are that the city centre region is considered as starting and final locations for all trips. This is done is account partly for the importance of door-to-door mobility where it is advantageous for the first travel terminal to be close to the start location. The expectation is that this will significantly affect flight waiting times more than train waiting times.

The model used for all simulations works as follows. Once the number of passengers to be shifted is received as input, relevant data points from the previous phase (capacity analysis) are used in order to gauge the effect on the change of number of flights and trains, based on the passenger cutoff and capacity per trip. This means that removing only 5 or 10 passengers from flights is likely to have negligent effects on the situation, however removing 100 passengers will likely result in a flight being cancelled and the result being that all passengers on that flight would have to be shifted. This is due to the strong assumption that all passengers travel using any mode to the destination in a closed system. Modelling effects due to cancellation or demand and supply were seen as being beyond the scope of this project.

The model will be used to evaluate two distinct scenarios for every (bidirectional) city pair. The first scenario is levying a tax on flight cost to the passenger, depending on the distance flown. The parameter **tax_per_distance_flown** will be varied from 0.05 EUR/km to 0.30 EUR/km to see the effect this has on carbon dioxide emissions in kilogram per passenger and change in waiting time per passenger in minutes. This scenario will make use of a research study that was recently conducted that found that 0.489% of passengers decided not to fly when the flight ticket was taxed with EUR 1, 00 [22].

The second scenario will investigate what the effect of targeted marketing towards incentivising a shift from flying to using the train could have on the closed travel situation. The parameter of passenger shift percentage will be varied from 5% to 25%. Different forms of marketing such as displaying the carbon dioxide emissions savings per passenger, or improved passenger experience as a result of less waiting time and friction, could be successfully used in the near future. This is the motivation for testing out this scenario.

For every (bidirectional) city pair, the results from running the model through the two scenarios will be presented. Only when necessary, will results from both directions be discussed, as it is expected that the difference between directions for the result of a city pair will be negligible.

E. Assumptions

For both the capacity analysis and modelling, several assumptions are made throughout the project. These assumptions make it possible to use the proposed approach for each part without the requirement of needing to find exact figures from official sources. From the start, the approach assumes that the scenarios and situations considered will be consistent between runs i.e. two train services will operate with the same number of carriages and same number of passenger seats per carriage.

Starting with estimating the capacity of flights, the figure of number of seats for the given typecode of the plane is derived by assuming around 80% of the maximum number of seats possible in a configuration. Most figures for maximum seats were obtained from OpenAP [21]. In addition, there can be multiple airports and therefore air routes possible between two cities. To account for this, a weighted average capacity is calculated and used in further analysis; this value takes into account for differences in the capacity and frequency of the different air routes.

For the train capacity analysis, finding the capacity information for the number of carriages and passengers per carriage is trickier due to variations in how train operators assemble their trains for different services. In order to keep the analysis simple, any values derived are to be consistently used throughout. While it was initially difficult to find detailed information about carriages used for the train services between the three city pairs, in the end the author was able to obtain information from public sources such as vagonWEB [23]. While different carriage types can have varying amounts of capacities, this was streamlined. It is assumed that every carriage has the same capacity and ensured that the total capacity (number of carriages multiplied by capacity per carriage) matches the total capacity from the public source.

Table 6 shows the (assumed) values used for the capacity analysis and further model.

Table 6: Assumption values for train and flight capacity analysis for the three city pairs

Assumptions	**AMS — LON**	**BER — FRA**	**PAR — TOU**
Number of carriages	15	12	8
Passengers per carriage	60	69	63
Utilisation	40%	55%	80%
Weighted capacity per flight	152	209	170

In addition to these assumptions, some other general assumptions are made for the model. For total CO_2 emission calculations, these are done using the mass and 'high' configuration passenger count of the plane type for the air route with the most passengers. The figure determined depends on the mass and distance travelled.

For trains, a different approach is used. The electrical energy for a train with an 'high' configuration of about 0.05 kWh per passenger kilometre is assumed. Then, a figure representing the CO_2 emissions on average to produce one kWh in the 27 EU countries is used to approximate the total emissions per train service (also dependant on travel distance).

The last assumptions used throughout the study are to do with the time components that were determined that build up the total waiting time from A to B for the three city pairs. For every time component, with exception of the travel time of either the train or flight, an upper and lower bound corresponding to a worst and best case respectively, were considered.

IV. Results & Discussion

A. Capacity analysis

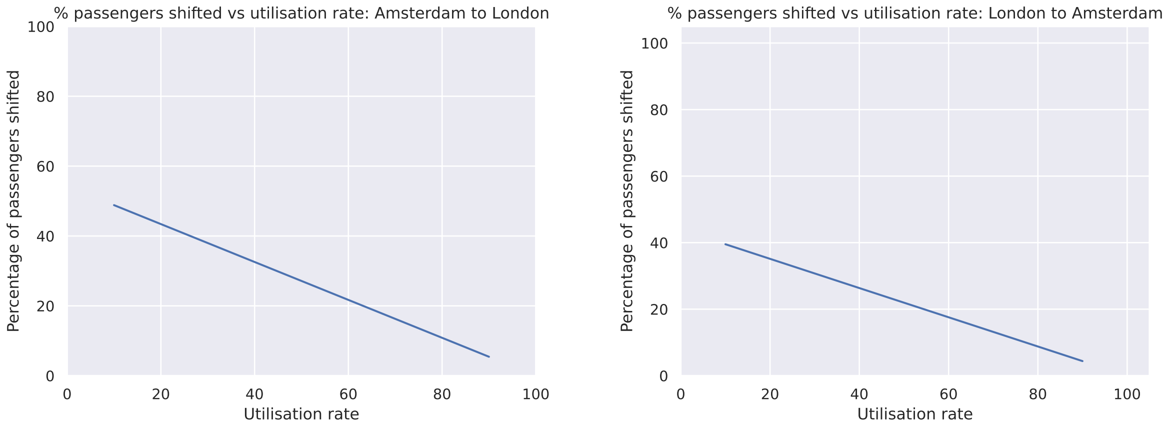
For every city pair, the results from the capacity analysis will be presented. This will follow the baseline results for every city pair where the number of flights, trains and passengers on each will be highlighted. The meaning of the results will be discussed at the city pair level.

1. Amsterdam — London

The city pair Amsterdam — London was an important city pair for this research as it is the route with the most number of daily flights in March 2019, as determined at the end of the processing data stage.

Table 7: Capacity analysis results for Amsterdam — London

Amsterdam — London	Flight	Train
Travel distance	340 km	360 km
Travel time	53 min	269 min
Utilisation (assumed)	N/A	40%
Trips per day	54	5
(Adjusted) capacity per day	8293 pax	2700 pax



(a) Amsterdam to London

(b) London to Amsterdam

Figure 4: Extent of feasibility of shifting passengers for Amsterdam — London

Table 7 shows the main capacity analysis results. The travel distance, time, utilisation, trips per day and adjusted capacity per day are included. In the table, adjusted capacity is capacity that can be added to trains given the mentioned utilisation. This means that even with the assumed 40% of utilisation on the train routes, about 35% of passengers from flights (about 3000 passengers) can be shifted to trains at a maximum.

It can be seen that the travel time of the train route is considerably higher than the time of the flight route. Even though this could be seen as a strong disadvantage for passengers to use the train, this time does not yet take into account the total door-to-door travel time.

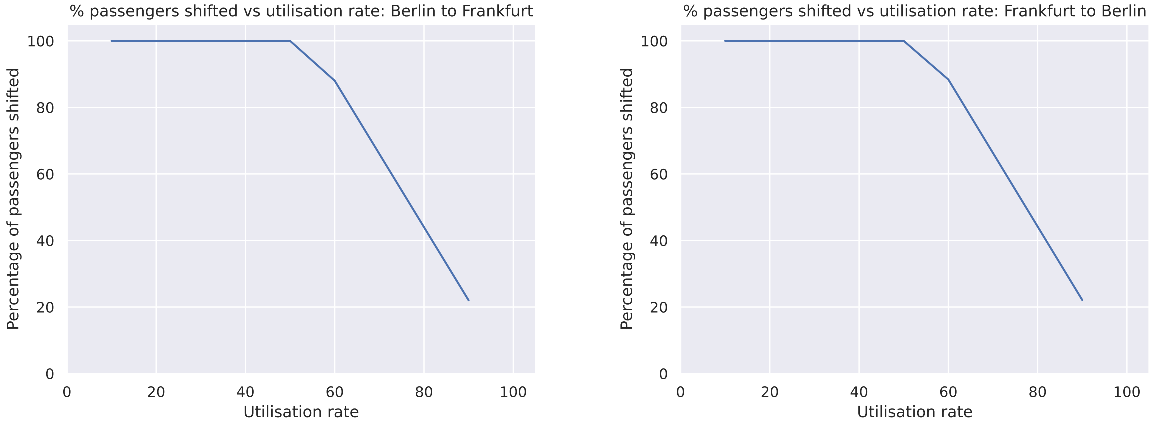
Figures 4(a) and 4(b) show a visualisation of how the extent of shifting passengers from flight to train changes with the utilisation rate of the train trips. As is expected, it is an inversely-proportional relationship between these variables. It can be noted here that AMS — LON has a slightly larger shift potential at lower utilisation rates compared to LON — AMS.

2. Berlin — Frankfurt

The second city pair that was considered was Berlin — Frankfurt. This route also had a high number of flights per day and this was the busiest route in domestic airspace in Germany in March 2019.

Table 8: Capacity analysis results for Berlin — Frankfurt

Berlin — Frankfurt	Flight	Train
Travel distance	460 km	430 km
Travel time	59 min	260 min
Utilisation (assumed)	N/A	80%
Trips per day	25	10
(Adjusted) capacity per day	5268 pax	1656 pax



(a) Berlin to Frankfurt

(b) Frankfurt to Berlin

Figure 5: Extent of feasibility of shifting passengers for Berlin — Frankfurt

Table 8 shows the results of the capacity analysis. It can be seen notably that even after assuming a very high utilisation rate of 80% for the train, it is still possible to shift above 40% of passengers from flights to trains, which is a very good result.

Figures 5(a) and 5(b) also show that especially at low utilisation rates below 50%, it is possible for all passengers to be shifted to trains from flights.

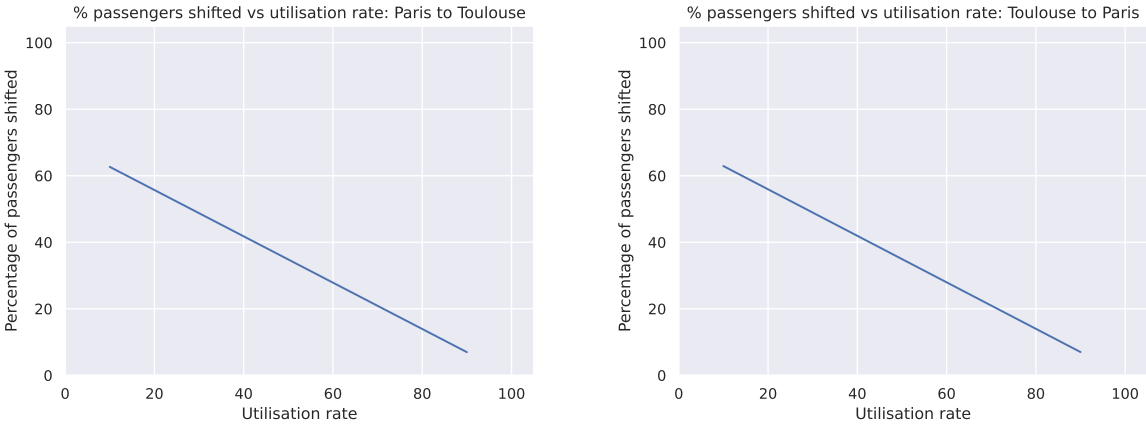
3. Paris — Toulouse

Lastly, the third city pair of Paris — Toulouse was considered. This city pair also had a high number of daily flights and was a prime candidate for this capacity analysis.

Table 9: Capacity analysis results for Paris — Toulouse

Paris — Toulouse	Flight	Train
Travel distance	625 km	587 km
Travel time	74 min	258 min
Utilisation (assumed)	N/A	55%
Trips per day	34	11
(Adjusted) capacity per day	5791 pax	2495 pax

Through Table 9 and Figures 6(a)/6(b), it is clear that the feasibility of shifting passengers follows a very similar pattern to the results from the analysis of Amsterdam — London. The main difference is that here there is a much larger percentage of passengers that can get shifted for a given utilisation rate.



(a) Paris to Toulouse (b) Toulouse to Paris

Figure 6: Extent of feasibility of shifting passengers for Paris — Toulouse

4. Final remarks

Overall, the results of the capacity analysis that was carried out for these three city pairs was very promising. A percentage range of 30-60% of shift possibility signals that it should be very feasible to shift passengers from flights to trains in these regions, in theory.

Of course, the practical effects have not been taken into account here and no conclusion of a practical nature can thus be made. The assumption that it is trivial to handle the influx of passengers from flights to trains has to be tested, and may not hold true at all times of the day or at all segments of the train trip and network.

B. Model simulations

Lastly, the results of the simulations run on two different scenarios for every city pair will be shown. After the results have been presented, a discussion on all results will be made to identify trends and explain any patterns on a macro scale with respect to the model simulations.

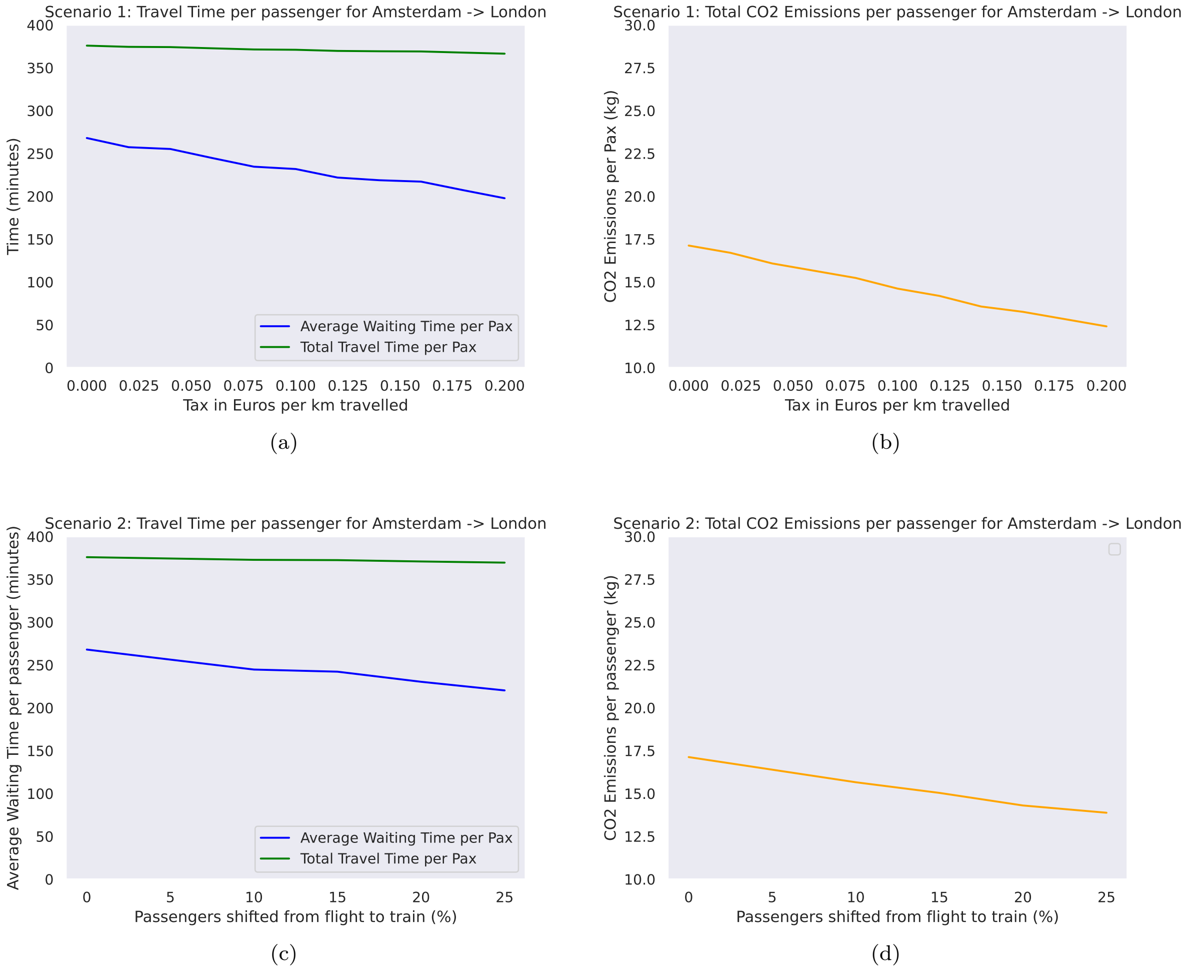
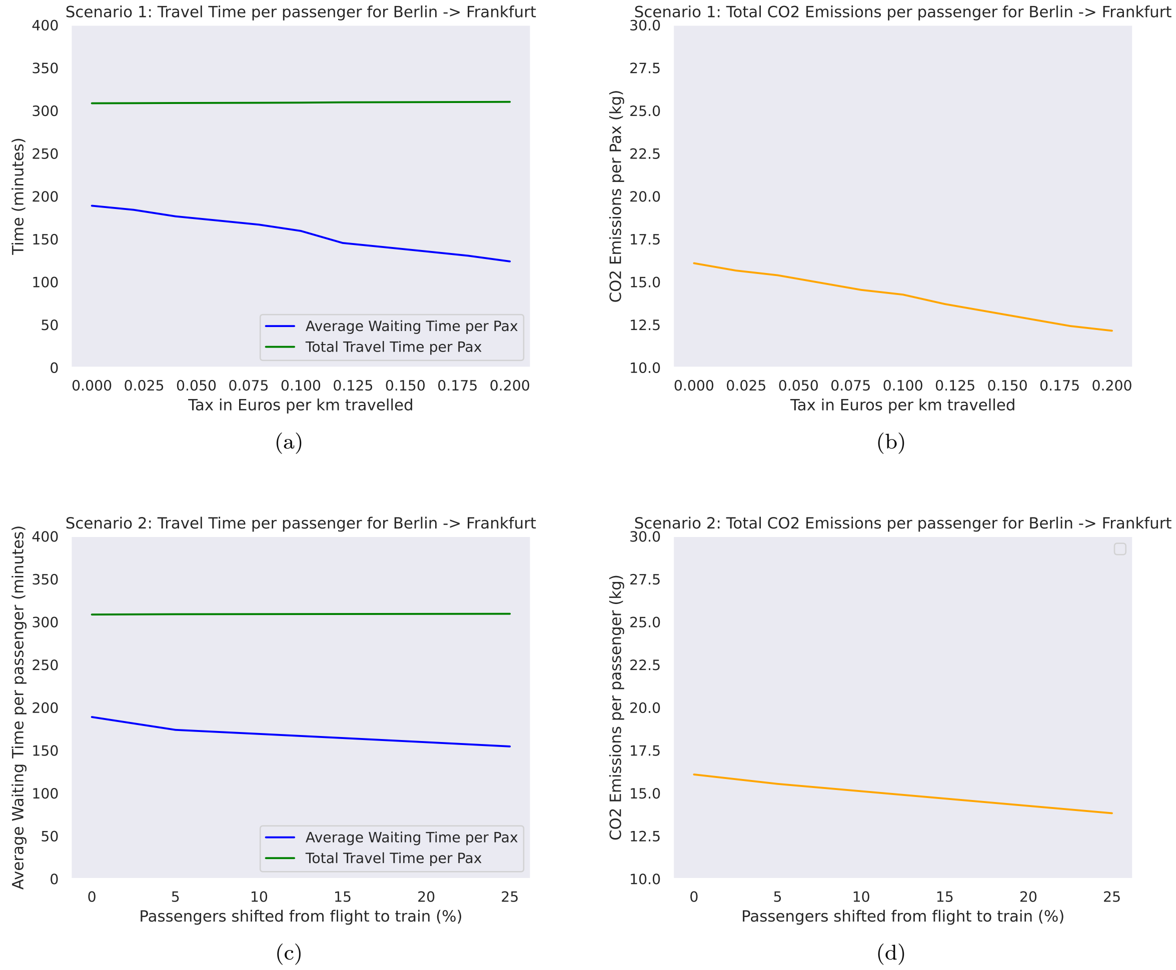
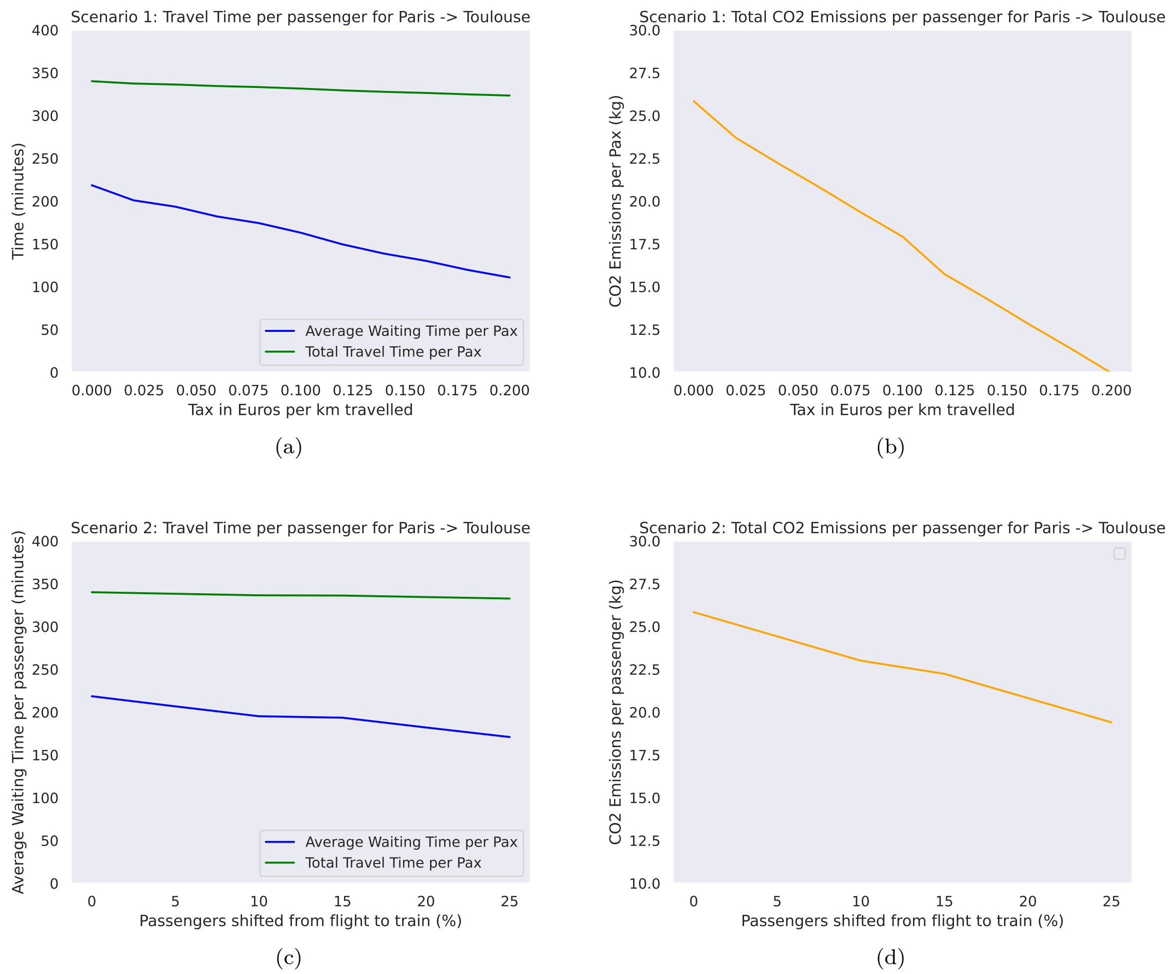


Figure 7: Results from model simulations for Amsterdam — London



(a) (b) (c) (d)

Figure 8: Results from model simulations for Berlin — Frankfurt



(a) (b) (c) (d)

Figure 9: Results from model simulations for Paris — Toulouse

Figures 7, 8 and 9 show the results from the simulations of the two scenarios, restricted to one direction for the three city pairs. Looking at the results from Scenario 1, which was the levying of a tax amount on flight tickets per kilometre of travel distance, it can be seen that the average waiting time per passenger were all linear with discontinuities and change in slope throughout. The change in slope indicates when a flight was no longer scheduled to travel in the simulation due to the number of passengers being lower than the cutoff after a shift. The number of slope changes is significantly higher for Amsterdam to London in comparison to the other two city pairs. This confirms that for the same amount of tax euros per km, the decrease in number of flights is reached quicker and that Amsterdam to London has more flights per day than the other two city pairs.

On the same graphs, the total travel time per passenger is also plotted. This indicator is calculated taking into account the proportion of passengers travelling on flights and trains for every situation. It can be noted the overall trend is similar between scenarios for the same city pair. In particular for Amsterdam to London and for Paris to Toulouse, a slight negative trend is observed where an increase of tax per kilometre or passengers shifted results in a slight decrease of total travel time per passenger. This suggests that the total travel time for train passengers is slightly lower than the total travel time for flight passengers. The opposite is only seen for Berlin to Frankfurt where instead an increase of total travel time can be seen. This can be explained by an higher total travel time for train passengers compared to flight passengers in this region. The main takeaway is that differences in travel time using the train or flight option still have far-reaching effects when looking at total travel time.

When looking at the change in magnitude of the average waiting time for all city pairs, it can be seen that even an increase of 0.10 EUR per km results in a difference of about 40-60 minutes across the board.

This is quite a significant result and confidently portrays that overall passenger experience has improved. This trend is also seen for Scenario 2, with a shift of just 15% of passengers due to marketing resulting in about 40 minutes decrease in waiting time per passenger across the board.

The carbon dioxide emissions per passenger also experiences a decrease with increased tax in EUR per km or a shift in passengers due to marketing. It is however less pronounced when looked at per passenger, due to the sheer number of flights and their total emissions staying on the larger side even after shifts in passengers. Nonetheless, a decrease of about 4 - 5 kg carbon dioxide emissions per passenger is observed across the board; a significant improvement when the total reduction in emissions is considered.

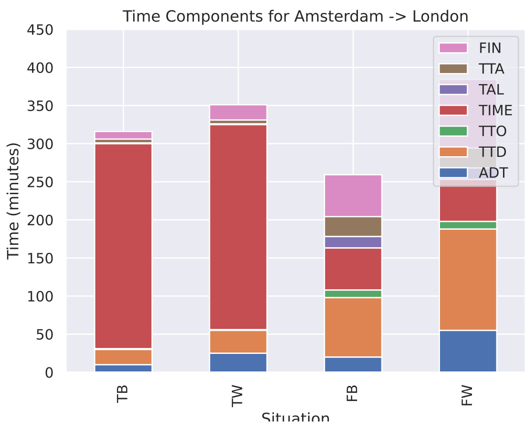
Overall, these results paint a positive picture of the possibilities and results of shifting passengers from flights to trains in different practical situations. Especially in the perspective of legislators, a taxation strategy can be useful. This also applies to airlines and train providers who can possibly work together in the near future on marketing for shifts and profit in a net positive result from these shifts.

C. Sensitivity analysis

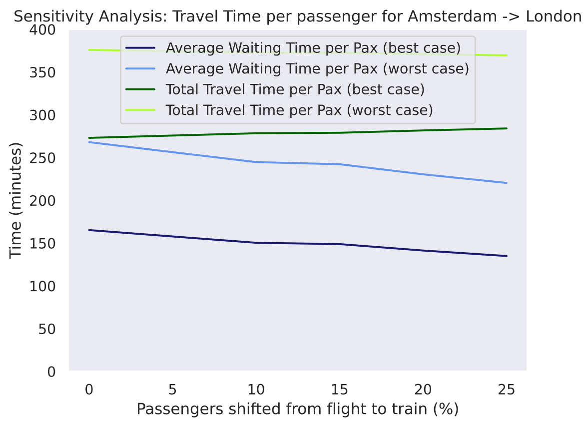
A limited sensitivity analysis was carried out in this study. The main parameters that were tested were varying the time components between a best case and worst case scenario. It is important to note that in all previous modelling, the worst case scenario was considered.

For each city pair, the time components, with exception of the main travel time, had best case and worst case bounds. The time component breakdown for the best and worst cases for the train and flight options, alongside a graph of total travel time and average waiting per passenger for these cases, are shown in Figures 10, 11 and 12.

In the graphs, TB, TW, FB, and FW refer to Train (best case), Train (worst case), Flight (best case) and Flight (worst case), respectively.

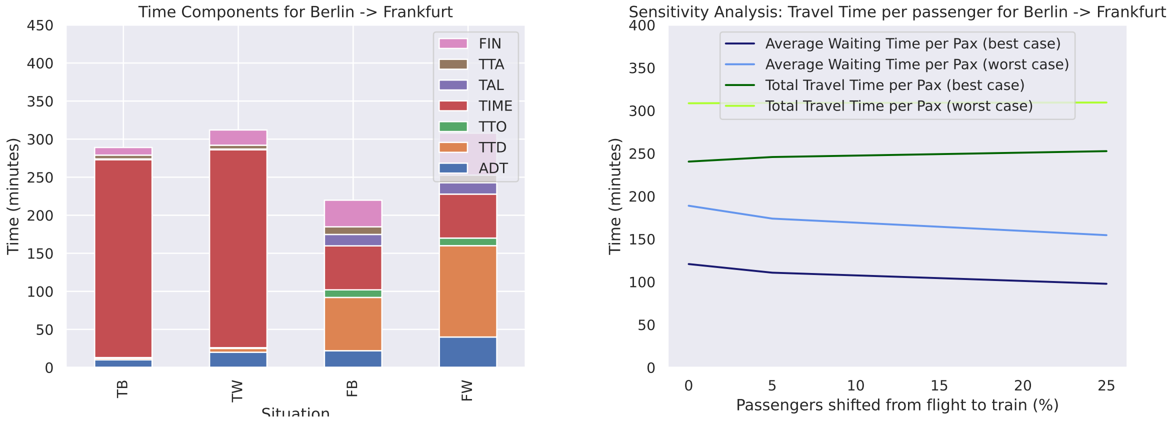


(a)



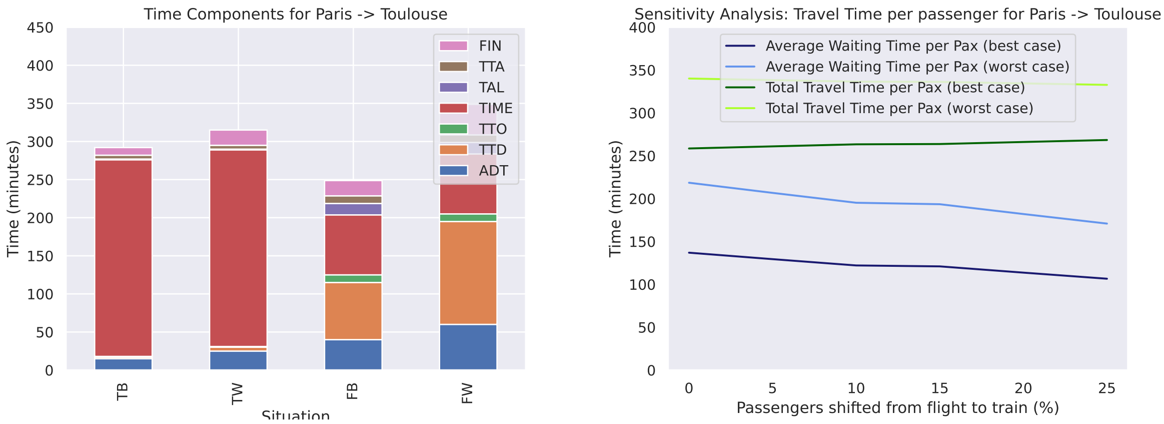
(b)

Figure 10: Results from sensitivity analysis for Amsterdam — London



(a) (b)

Figure 11: Results from sensitivity analysis for Berlin — Frankfurt



(a) (b)

Figure 12: Results from sensitivity analysis for Paris — Toulouse

It can be seen for all city pairs that the proportion of travel time on the train is significantly larger part of the total travel time, than it is on the flight. Still notably, the other waiting components for train trips in both the best or worst cases are far smaller than the waiting components for any flight trips.

The main takeaway from the time components is that for all train trips, the margin to reduce the waiting time is very limited in comparison to the flight trips. This means that in the short term it is more difficult to reduce the total travel time by train than by flight. The assumption here is that reducing the travel time for the different modes can only be achieved long term and is more difficult to achieve.

When looking at the graphs, it can be seen that the trend changes when looking at total travel time per passenger for the best case over the worst case. This confirms that flight passengers benefit from a decrease in waiting time to a larger extent compared to train passengers. In addition, across the board, there is a decrease of about 75 — 100 minutes in both total travel time and average waiting time per passenger for both modes when considering the best case over the worst case scenario.

This sensitivity analysis shows that considering different combinations of waiting time and total travel time can make a significant different to the results achieved when shifting passengers from flights to trains. In the short term, flight passengers experience quicker trips due to waiting time decreases compared to train passengers.

V. Conclusion & Recommendations

While the results and succeeding conclusion may now prompt more follow up questions about how one would use this research in the practical environment to advise and form strategy for better shared and door-to-door mobility, it is important to recognise the main contribution of this research.

This research set out to investigate the feasibility and logistics of multi-modal transport and to build an reproducible approach with open principles from the start. The methodology, results and discussion that have been presented are evidence that this approach and research method is possible with only openly accessible data.

While there can still be limitations with how some of the data is used in this research, the approach presented in this paper is quite flexible and can be as accurate as the data that is provided as input. As such, this approach has the strong potential to be expanded and adapted to an environment where more accurate data is present.

The focus of this paper has been more on the research methodology and less on the practical effects and implications of the results obtained. This was done intentionally. It was important to the author to ensure that the method had a solid base and that it could be built on further in possible future research.

It was also important to look at distinct geographic regions to really gauge the feasibility of shifting passengers on a macro scale. The result that about 30-50% of passengers could be shifted from flights to trains, given that the train network can handle the shift, is a very positive outcome in this research space.

That being said, it would benefit further studies to delve more deeply into the logistics of implementing this shift in a more specific case study. While there are already studies looking at flight bans, there is very limited research on the logistics behind facilitating such a shift. Ensuring that either the flight or train network is not overloaded during a shift operation is a very important aspect that must not be overlooked.

Another positive outcome of this research is the reduction of total carbon dioxide emissions as a result of large scale shifts of passengers from flights to trains. This is more important now with researchers looking to find different effective ways of reducing overall emissions in the aviation sector. Shifting passengers on a large scale in multiple regions could help to kick-start a short-term reduction in carbon dioxide emissions through the use of taxation, marketing, or other strategies.

Another aspect which has not been taken into consideration much in this research space is passenger experience. While passenger experience is qualitative and measuring it can be very difficult, it is still possible to make use of meaningful indicators, such as was done in this study with total travel time and average waiting time per passenger. The effect of shifting passengers is two-fold: both train and flight passengers can benefit with lower waiting times and an objectively better experience with a less crowded airport terminal. However, more research must still be done on whether there is an extent to which shifting more passengers leads to an eventual drop-off in passenger experience.

References

[1] Lieshout, R., Malighetti, P., Redondi, R., and Burghouwt, G., "The competitive landscape of air transport in Europe," *Journal of Transport Geography*, Vol. 50, 2016, p. 68–82. doi:10.1016/j.jtrangeo.2015.06.001, https://dx.doi.org/10.1016/j.jtrangeo.2015.06.001.

[2] Robertson, S., "The potential mitigation of CO2 emissions via modal substitution of high-speed rail for short-haul air travel from a life cycle perspective – An Australian case study," *Transportation Research Part D: Transport and Environment*, Vol. 46, 2016, p. 365–380. doi:10.1016/j.trd.2016.04.015, https://dx.doi.org/10.1016/j.trd.2016.04.015.

[3] Delgado, L., Bolić, T., Cook, A., Zareian, E., Gregori, E., and Paul, A., "Modelling passengers in air-rail multimodality," -, 2023. doi:10.5281/ZENODO.8385515, https://zenodo.org/record/8385515.

[4] Delgado, L., Trapote-Barreira, C., Montlaur, A., Bolić, T., and Gurtner, G., "Airlines' network analysis on an air-rail multimodal system," *Journal of Open Aviation Science*, Vol. 1, No. 2, 2023. doi:10.59490/joas.2023.7223, http://dx.doi.org/10.59490/joas.2023.7223.

[5] Chen, Y., "Modeling and analyzing the environmental impact of short-to-medium range air and ground transports," https://repository.tudelft.nl/islandora/object/uuid%3Ac2c3a5e3-9f75-4fb6-83ca-29b474d7e8c6?collection=education, 2023.

[6] Bislip, K., "Streamlining multi-stop flights with ground transportation," https://repository.tudelft.nl/islandora/object/uuid%3A909e41a6-ede4-487a-afe6-613ff6ed58fa?collection=education, 2023.

[7] Brons, M., *Price Elasticities of Demand for Passenger Air Travel*, 2001. https://papers.tinbergen.nl/01047.pdf.

[8] Cantos-Sánchez, P., Moner-Colonques, R., Ruiz-Buforn, A., and Sempere-Monerris, J. J., "Welfare and environmental effects of short-haul flights bans," *Transport Economics and Management*, Vol. 1, 2023, p. 126–138. doi:10.1016/j.team.2023.08.002, http://dx.doi.org/10.1016/j.team.2023.08.002.

[9] SESAR JU, *SESAR Joint Undertaking | New EU SESAR project, MultiModX, kicks off to enhance multimodal transport networks — sesarju.eu*, 2022. https://www.sesarju.eu/news/new-eu-sesar-project-multimodx-kicks-enhance-multimodal-transport-networks.

[10] "Final Report Summary - METPEX (A MEasurement Tool to determine the quality of the Passenger EXperience) | FP7 | CORDIS | European Commission — cordis.europa.eu," https://cordis.europa.eu/project/id/314354/reporting, 2015.

[11] Diana, M., Pirra, M., Castro, A., Duarte, A., Brangeon, V., Di Majo, C., Herrero, D., Hrin, G. R., and Woodcock, A., "Development of an Integrated Set of Indicators to Measure the Quality of the Whole Traveller Experience," *Transportation Research Procedia*, Vol. 14, 2016, p. 1164–1173. doi:10.1016/j.trpro.2016.05.187, http://dx.doi.org/10.1016/j.trpro.2016.05.187.

[12] Susilo, Y. O., and Cats, O., "Exploring key determinants of travel satisfaction for multi-modal trips by different traveler groups," *Transportation Research Part A: Policy and Practice*, Vol. 67, 2014, p. 366–380. doi:10.1016/j.tra.2014.08.002, http://dx.doi.org/10.1016/j.tra.2014.08.002.

[13] Herrero Tomás, M. D., and González Viosca, E., "ANALYSIS OF THE QUALITY OF THE WHOLE JOURNEY (DOOR-TO-DOOR) PASSENGER EXPERIENCE," *Libro de Actas CIT2016. XII Congreso de Ingeniería del Transporte*, Universitat Politècnica València, 2016, pp. 1–9. doi:10.4995/cit2016.2016.4083, http://dx.doi.org/10.4995/cit2016.2016.4083.

[14] Jiang, M., Jiang, C., Xiao, Y.-b., and Wang, C., "Air-HSR cooperation: Impacts on service frequency and environment," *Transportation Research Part E: Logistics and Transportation Review*, Vol. 150, 2021, p. 102336. doi:10.1016/j.tre.2021.102336, http://dx.doi.org/10.1016/j.tre.2021.102336.

[15] Chiambaretto, P., and Decker, C., "Air–rail intermodal agreements: Balancing the competition and environmental effects," *Journal of Air Transport Management*, Vol. 23, 2012, p. 36–40. doi:10.1016/j.jairtraman.2012.01.012, http://dx.doi.org/10.1016/j.jairtraman.2012.01.012.

[16] Suau-Sanchez, P., Voltes-Dorta, A., and Cugueró-Escofet, N., "An early assessment of the impact of COVID-19 on air transport: Just another crisis or the end of aviation as we know it?" *Journal of Transport Geography*, Vol. 86, 2020, p. 102749. doi:10.1016/j.jtrangeo.2020.102749, https://dx.doi.org/10.1016/j.jtrangeo.2020.102749.

[17] EUROCONTROL, *Aviation Data Repository for Research - Metadata*, Jun. 2023. https://www.eurocontrol.int/sites/default/files/2023-07/rnd-data-description-2023.pdf.

[18] OurAirports.com, *OurAirports CSV Dataset*, 2024. https://ourairports.com/airports.csv.

[19] GTFS.org, *Reference - General Transit Feed Specification*, Jun. 2024. https://gtfs.org/schedule/reference/.

[20] Morgan, M., *UK2GTFS: Converts UK transport timetable datasets to GTFS format*, 2024. https://github.com/itsleeds/uk2gtfs, r package version 0.2.1, https://itsleeds.git.io/uk2gtfs/.

[21] Sun, J., *OpenAP - Open Aircraft Performance Model and Python Toolkit*, Jun. 2024. https://github.com/TUDelft-CNS-ATM/openap.

[22] CE Delft, *Impact of an increase in air passenger tax - CE Delft*, 09 2022. https://cedelft.eu/publications/impact-of-an-increase-in-air-passenger-tax/.

[23] vagonWEB, *vagonWEB :: Railway passenger cars*, 2024. https://www.vagonweb.cz/.

[24] IATA, *IATA - Level of Service Concept*, 2024. https://www.iata.org/en/services/consulting/airport-pax-security/level-of-service/.

A. Other figures

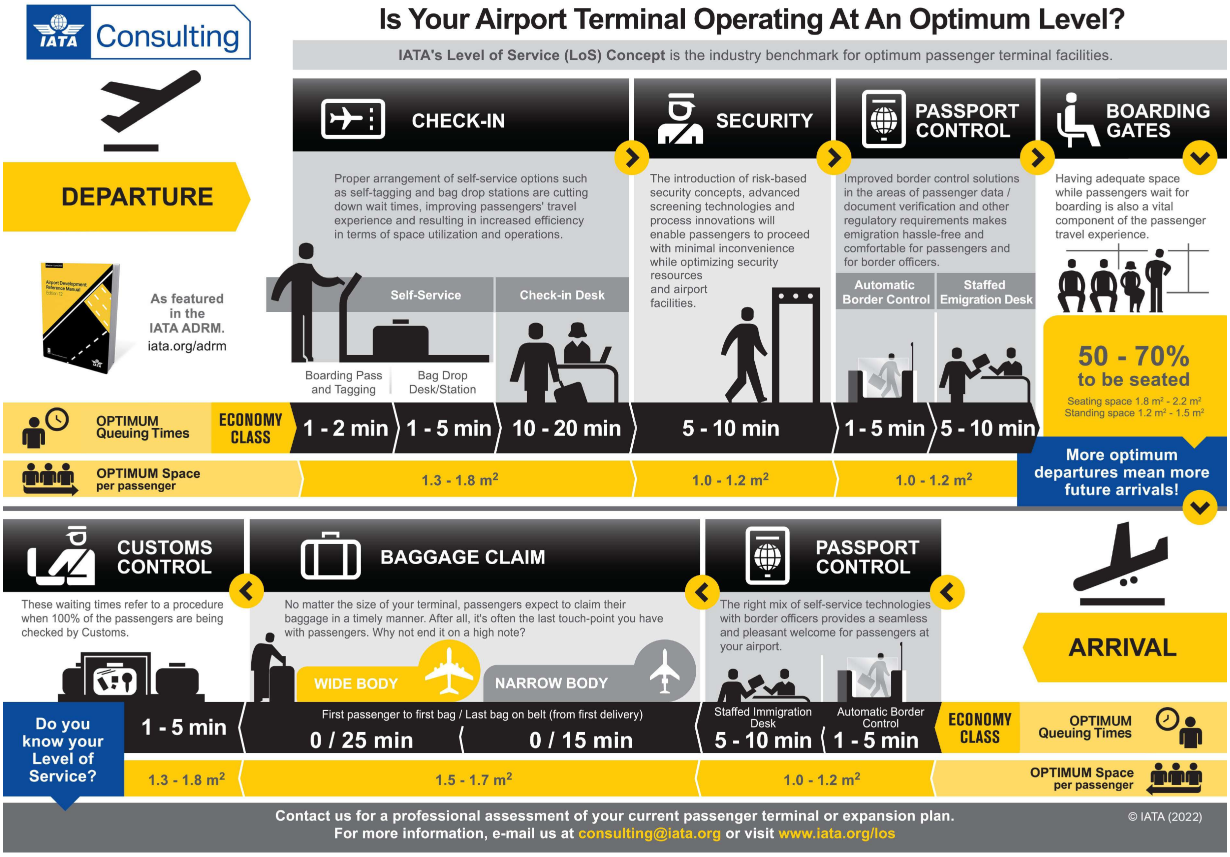


Figure 13: IATA airport terminal planning infographic [24]

II

Other Documents

*A selection of documents used in presentations and reports throughout the thesis project.

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Thesis time planning and logistics: overall planning

MSc Thesis Planning								
November							MSc Thesis Week	Holiday (+TU) Week
Mon	Tue	Wed	Thu	Fri	Sat	Sun		
30	31	1	2	3	4	5		
6	7	8	9	10	11	12	1	
13	14	15	16	17	18	19	2	
20	21	22	23	24	25	26	3	
27	28	29	30	1	2	3	4	
December								
4	5	6	7	8	9	10	5	
11	12	13	14	15	16	17		1
18	19	20	21	22	23	24		2
25	26	27	28	29	30	31		3 (TU)
January								
1	2	3	4	5	6	7		4 (TU)
8	9	10	11	12	13	14	6	
15	16	17	18	19	20	21	7	
22	23	24	25	26	27	28	8	
29	30	31	1	2	3	4	9	
February								
5	6	7	8	9	10	11	10	
12	13	14	15	16	17	18	11	
19	20	21	22	23	24	25	12	
26	27	28	29	1	2	3	13	
March							MSc Thesis Week	Holiday (+TU) Week
4	5	6	7	8	9	10	14	
11	12	13	14	15	16	17	15	
18	19	20	21	22	23	24	16	
25	26	27	28	29	30	31	17	
April								
1	2	3	4	5	6	7	18	
8	9	10	11	12	13	14	19	
15	16	17	18	19	20	21	20	
22	23	24	25	26	27	28	21	
29	30	1	2	3	4	5	22	
May								
6	7	8	9	10	11	12	23	
13	14	15	16	17	18	19	24	
20	21	22	23	24	25	26	25	
27	28	29	30	31	1	2	26	
June								
3	4	5	6	7	8	9	27	
10	11	12	13	14	15	16	28	
17	18	19	20	21	22	23	29	
24	25	26	27	28	29	30	30	
July								
1	2	3	4	5	6	7	31	
8	9	10	11	12	13	14	32	
15	16	17	18	19	20	21		
22	23	24	25	26	27	28		
29	30	31	1	2	3	4		

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Research Proposal

Modelling and investigating the feasibility and logistics of multi-modal transport

by

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Date: January 12, 2024

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1. Introduction

In recent years, the European Commission, meeting in line with the objectives of the European Green Deal, has started work on increasing connectivity between rail networks and promoting more sustainable travel through its aim of placing a stronger focus on sustainable urban mobility [1]. They envision the TEN-T network of various EU-wide ground routes to bring significant advantages to ground transport options between more than 400 major cities by 2040. However, there are currently very dense air networks of low-cost, high-frequency short-haul flights between many cities.

Although air transport provides passengers with convenient transportation options due to its high operational density, it is crucial to emphasise that aviation still contributes very significantly to transportation emissions. Research indicates that short-haul air transport emits a considerably higher amount of greenhouse gases (GHG) per passenger kilometre compared to most ground transportation methods [2] [3].

In recent years, the effects of air-rail competition and cooperation have been studied extensively [4] [5], and it has been shown that inter-modal trips with a combination of an air segment and rail segment can bring benefit to travellers and help with reducing environmental impact. However, it is important to investigate the logistics of shifting passengers from air segments to ground-based travel segments, in order to gauge the extent to which these shifts can take place in a multi-modal trip without a significant change to total travel time.

The objective of this research is to accurately determine the capacity of air and ground transport networks in regions of key interest, capture key factors such as total travel time and passenger experience in a model, and use this model to investigate the feasibility of shifting passengers from short-haul flight segments to ground segments in a multi-modal trip.

The results from this research will then be used to develop an approach that optimises for an alternative multi-modal trip that has the least impact on the environment through emissions, while still ensuring similar total travel time and passenger experience.

The findings from this work can help transport providers and those developing ground infrastructure as they will be able to gauge how much capacity ground transport networks can facilitate, and how much of a shift is possible from air based routes, while maintaining passenger experience levels through any shifts. In addition, with legislation in many countries calling for a ban on short-haul flights under specific travel times or distances, it can form as a valuable insight into the effects and consequences of enforcing such a ban on ground transport networks and whether the infrastructure can handle a sudden influx of passengers shifting from air transport.

In particular, the research questions and objectives will be presented in the research plan in Chapter 2, which will also delve into the different phases of research and the methodology that will be used during the research. This is followed by a brief review of the current state of the art research on multi-modal trips and network capacity analysis in Chapter 3. Finally, this research proposal will be concluded in Chapter 4.

2. Research Plan

The research questions and sub-questions will be presented in this chapter. In addition, the main objectives of the research will also be discussed. Later, the research will be broken down into phases and the research activities belonging to each phase explained. Finally, an overview chart of the research approach and time planning will be presented.

2.1. Research Questions

The main research questions and sub-questions that the research aims to solve are,

1. What is the extent to which passengers on short-haul flight segments can be shifted to ground transport segments in a multi-modal trip without a significant increase in total travel time and cost, in a given region?
    - How to measure effects due to inter-modality across multi-modal trips and different transport providers?
    - How to accurately determine the capacity of air and ground transport networks, capture this information in a model, and use the model to inform possible policy changes and infrastructural decisions?
2. When selecting possible shifts from short-haul flight segments to ground segments in a multi-modal trip, what is the best method that can be used to optimise for shifts with minimal environmental impact and lower travel cost and time?
    - What is the extent to which widespread passenger choice for air or ground transport influences the feasibility of a shift?
    - What factors of a multi-modal trip influence passenger choice for a multi-modal trip over a direct trip?

2.2. Research Objectives

1. Develop a method to accurately determine the capacity of air and ground transport networks in regions of key interest
2. Develop and test an optimisation approach that allows to route and plan for multi-modal journeys (with one or more legs using ground transport) with minimal environmental impact, total travel and cost
3. Use the findings to advise the different stakeholders involved in the development and maintenance of transport networks on the best recommendations to boost shifts from air to ground transport in short-to-medium travel plans

2.3. Research Phases

The research activities that will be conducted as part of the thesis will be broken down into four research phases, for which each the activities of each will be described next.

2.3.1. Phase 1: Setup

The first phase of the research is to setup the research by obtaining data from various research sources on air routes and ground-based transport routes (including rail and bus networks). Data from selected countries including Germany, Italy, Spain, The Netherlands and France will be used as it has been determined that data on air and ground transport routes is readily available to the author, and most information has been made available by transport operators in these countries.

In addition, for Phase 2 and Phase 3, a diverse set of the busiest air and ground based routes will be chosen as a baseline to be used for research. In this way, the findings from the capacity analysis in Phase 2 can be used alongside the findings of Phase 3.

2.3.2. Phase 2: Capacity Analysis

The next phase of the research will involve performing capacity analysis on the aforementioned air and ground transport routes. For each of these routes, the region's (country, and inter-country) air transport and ground transport networks will be analysed to measure the capacity, in either direction, of travelling on the routes through these networks and to get an understanding for the differences in the number of passengers that can be transported via each network.

The results of the capacity analysis will allow for a deeper look into seeing how the capacity is spread throughout a region depending on the type of transport and serves as an early look into the feasibility for the routes that were chosen in Phase 1.

2.3.3. Phase 3: Build and refine extended model

Phase 3 will involve adding key parameters to the research model to reflect the multi-modal nature of trips. These include parameters such as cost, passenger experience, occupancy, lead waiting time or lead average connection time between segments, and total GHG per passenger.

Passenger experience is a factor that will be taken into account in the model and will reflect data on passengers' experience at the transport terminals of a given route. For instance, for a trip from Amsterdam to Munich via Frankfurt with the first segment via air transport and the second segment via ground transport, data taken from previous research on the experience of passengers at Schiphol Airport, Munich Airport, Munich Rail Station and Frankfurt Rail Station, will be considered. In addition, special weighting will be levied on the terminals used during a connection/switch of modes of transport.

After the revised model is built, simulations will be run alongside the previous capacity analysis, with the aforementioned chosen routes. Tests will be run and sensitivity analysis carried out in order to see the effect of changing different parameters (such as passenger choice and passenger experience) on the results obtained (total travel time, number of segments in the multi-modal trip, GHG per passenger km).

For further studies, constraints such as limiting flights to those only above 500 km, will be introduced to see the effect they may have on the multi-modal routes found. During the analysis, the effects of air-rail, rail-bus and air-bus connections will be investigated as well.

2.3.4. Phase 4: Logistics, analysis and recommendations

In the final phase, results and findings from previous phases will be used along with simulations run on a macro-scale with all routes between multiple countries in the region in order to understand the effects of shifting air to ground segments in a multi-modal trip with interchanging air and ground transport networks.

A large-scale and small-scale shifts, in the form of constraining limits on short-to-medium haul flights, will be levied to see the effect of the shifts on the networks as a whole. These findings will be analysed and used to form conclusions and recommendations to various stakeholders on the logistics of the better management and promotion of infrastructure in order to boost multi-modal transport.

2.4. Research Approach

The overall research approach is presented in Figure 2.1.

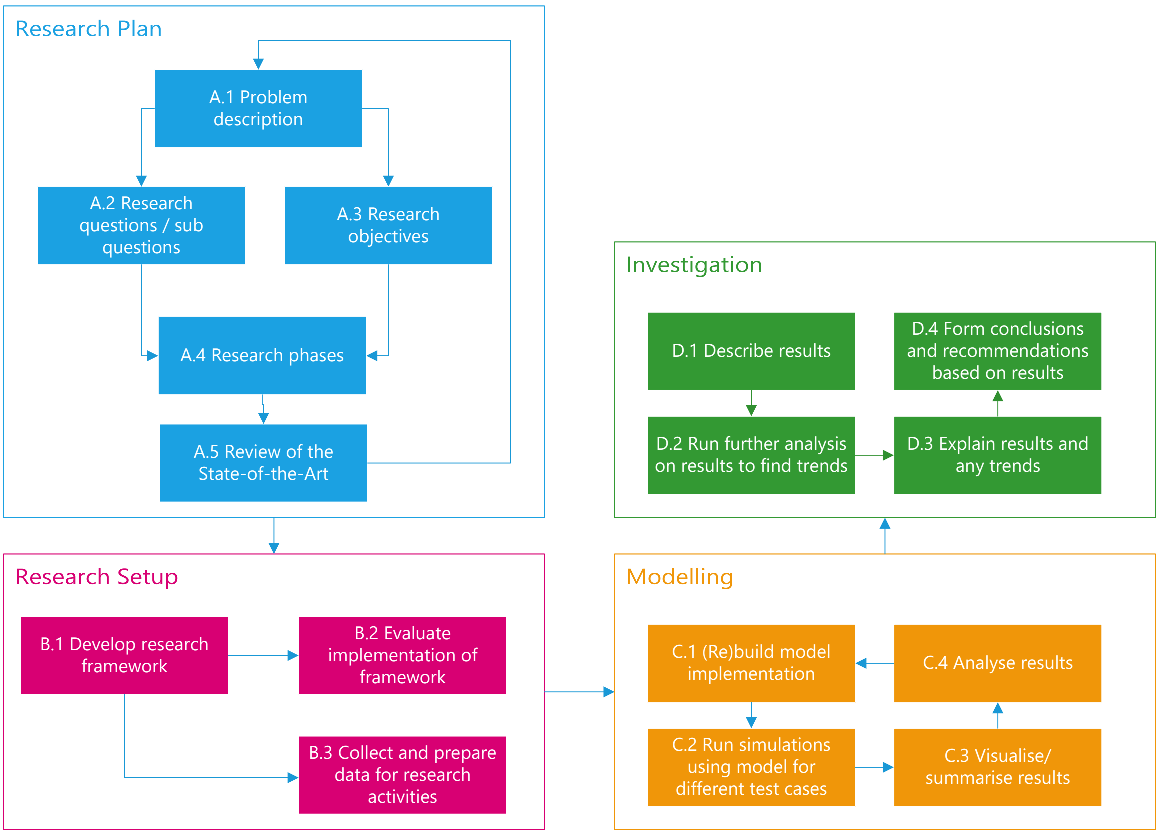

Figure 2.1: *Thesis Research Approach*

2.5. Time Planning

Phase 1, Phase 2 and a part of Phase 3 will be completed in the first research phase (as defined by the official AE Master Thesis Timeline), by the Midterm Review milestone.

The remainder of Phase 3 and Phase 4, and formal thesis matters will be completed by the Green Light Review milestone.

3. Review of the State-of-the-Art

3.1. Analysing capacity of transport networks

Analysing the capacity of transport networks is a crucial first step in determining the feasibility of multi-modal trips and understanding the underlying factors that affect it.

Since July 2023, the EU SESAR 3 Joint Undertaking partnership has launched an initiative called MultiModX (Integrated Passenger-Centric Planning of Multimodal Transport Networks) whose goal is to deliver a set of innovative multi-modal solutions and decision support tools for the coordinated planning and management of multi-modal transport networks [6]. MultiModX has fostered a lot of research in the space of multi-modal transport networks. Delgado et.al. [7] have also looked into modelling the integration between some air and rail networks and evaluating its effects.

In addition, several studies and previous theses ([7]–[10]) show that data obtained from OpenSky or EUROCONTROL for air transport, and GTFS or open schedule data published by ground transport providers can be used reliably for capacity analysis.

With the frequency information of flights, trains or buses and known passenger capacity numbers for different aircraft or vehicle configurations, capacity can be determined.

3.2. Measuring passenger experience

Passenger experience is generally thought about as being a qualitative factor and not necessarily something which can be directly quantified. Nevertheless, there have been several studies and approaches to measuring passenger experience in different transport networks, across complete journeys.

Notably, the METPEX (A MEasurement Tool to determine the quality of the Passenger EXperience) project [11] has published various papers [12]–[14] that go over the key factors that help to determine and quantify passenger experience in door-to-door journeys. In addition, factors such as user satisfaction and average waiting times at airports, rail stations and bus stations, can also contribute towards or detract from passenger experience.

3.3. Effects of air and ground transport inter-modality

Air and ground transport inter-modality effects including with respect to competition and cooperation between air and rail transport networks have been a subject of many studies in the past half-decade.

An important aspect of competition between air and rail transport is with the possible impact of HSR (High Speed Rail) based travel on flight frequency and demand. Jiang [15] found that introducing a low-cost HSR option to the Paris to Marseilles route reduced air traffic in the same route by 33%.

With respect to cooperation, Chiambaretto [5] found that over the past few years inter-modality agreements have brought upon significant benefits, including the stimulation of shifts from air to rail transport in many cases.

4. Conclusion

Research into the feasibility and logistics of multi-modal trips with emphasis into analysing transport networks' capacity is crucial in order to plan and for stimulate for better inter-modality between air and ground transport options as it becomes ever more important to promote sustainable urban mobility inline with the European Green Deal.

The research proposed aims to not only study and analyse the capacity of the transport networks to understand any logistical challenges facing a sudden shift of short-to-medium range flights to other modes of transport, but also aims to take into account passenger experience, cost and total travel time in order to present options that are practical alternatives to air transport.

With this research, infrastructure and ground transport providers can identify key points of their networks that need to be optimised for shifts from air transport networks and improve the throughput and passenger experience for future travellers.

The final research report will detail all the research activities and their findings, and provide key recommendations to the different stakeholders involved on the key items that demand improvement such that multi-modal trips with more ground based transport segments become the norm.

Bibliography

[1] *Efficient and Green Mobility — transport.ec.europa.eu*, https://transport.ec.europa.eu/news-events/news/efficient-and-green-mobility-2021-12-14_en, [Accessed 13-12-2023].

[2] S. Robertson, "The potential mitigation of co2 emissions via modal substitution of high-speed rail for short-haul air travel from a life cycle perspective – an australian case study," *Transportation Research Part D: Transport and Environment*, vol. 46, pp. 365–380, Jul. 2016, ISSN: 1361-9209. DOI: 10.1016/j.trd.2016.04.015. [Online]. Available: http://dx.doi.org/10.1016/j.trd.2016.04.015.

[3] *Carbon footprint of travel per kilometer — ourworldindata.org*, https://ourworldindata.org/grapher/carbon-footprint-travel-mode, [Accessed 08-01-2024].

[4] D. Albalate, G. Bel, and X. Fageda, "Competition and cooperation between high-speed rail and air transportation services in europe," *Journal of Transport Geography*, vol. 42, pp. 166–174, Jan. 2015, ISSN: 0966-6923. DOI: 10.1016/j.jtrangeo.2014.07.003. [Online]. Available: http://dx.doi.org/10.1016/j.jtrangeo.2014.07.003.

[5] P. Chiambaretto and C. Decker, "Air–rail intermodal agreements: Balancing the competition and environmental effects," *Journal of Air Transport Management*, vol. 23, pp. 36–40, Aug. 2012, ISSN: 0969-6997. DOI: 10.1016/j.jairtraman.2012.01.012. [Online]. Available: http://dx.doi.org/10.1016/j.jairtraman.2012.01.012.

[6] *SESAR Joint Undertaking | New EU SESAR project, MultiModX, kicks off to enhance multimodal transport networks — sesarju.eu*, https://www.sesarju.eu/news/new-eu-sesar-project-multimodx-kicks-enhance-multimodal-transport-networks, [Accessed 08-01-2024].

[7] L. Delgado, T. Bolić, A. Cook, E. Zareian, E. Gregori, and A. Paul, "Modelling passengers in air-rail multimodality," en, 2023. DOI: 10.5281/ZENODO.8385515. [Online]. Available: https://zenodo.org/record/8385515.

[8] L. Delgado, C. Trapote-Barreira, A. Montlaur, T. Bolić, and G. Gurtner, "Airlines' network analysis on an air-rail multimodal system," *Journal of Open Aviation Science*, vol. 1, no. 2, Nov. 2023, ISSN: 2773-1626. DOI: 10.59490/joas.2023.7223. [Online]. Available: http://dx.doi.org/10.59490/joas.2023.7223.

[9] Y. Chen, *Modeling and analyzing the environmental impact of short-to-medium range air and ground transports*, https://repository.tudelft.nl/islandora/object/uuid%3Ac2c3a5e3-9f75-4fb6-83ca-29b474d7e8c6?collection=education, 2023.

[10] K. Bislip, *Streamlining multi-stop flights with ground transportation*, https://repository.tudelft.nl/islandora/object/uuid%3A909e41a6-ede4-487a-afe6-613ff6ed58fa?collection=education, 2023.

[11] *Final Report Summary - METPEX (A MEasurement Tool to determine the quality of the Passenger EXperience) | FP7 | CORDIS | European Commission — cordis.europa.eu*, https://cordis.europa.eu/project/id/314354/reporting, 2015.

[12] M. Diana, M. Pirra, A. Castro, *et al.*, “Development of an integrated set of indicators to measure the quality of the whole traveller experience,” *Transportation Research Procedia*, vol. 14, pp. 1164–1173, 2016, ISSN: 2352-1465. DOI: 10.1016/j.trpro.2016.05.187. [Online]. Available: http://dx.doi.org/10.1016/j.trpro.2016.05.187.

[13] Y. O. Susilo and O. Cats, “Exploring key determinants of travel satisfaction for multi-modal trips by different traveler groups,” *Transportation Research Part A: Policy and Practice*, vol. 67, pp. 366–380, Sep. 2014, ISSN: 0965-8564. DOI: 10.1016/j.tra.2014.08.002. [Online]. Available: http://dx.doi.org/10.1016/j.tra.2014.08.002.

[14] M. D. Herrero Tomás and E. González Viosca, “Analysis of the quality of the whole journey (door-to-door) passenger experience,” in *Libro de Actas CIT2016. XII Congreso de Ingeniería del Transporte*, ser. CIT2016, Universitat Politècnica València, Jun. 2016. DOI: 10.4995/cit2016.2016.4083. [Online]. Available: http://dx.doi.org/10.4995/cit2016.2016.4083.

[15] M. Jiang, C. Jiang, Y.-b. Xiao, and C. Wang, “Air-hsr cooperation: Impacts on service frequency and environment,” *Transportation Research Part E: Logistics and Transportation Review*, vol. 150, p. 102 336, Jun. 2021, ISSN: 1366-5545. DOI: 10.1016/j.tre.2021.102336. [Online]. Available: http://dx.doi.org/10.1016/j.tre.2021.102336.

Midterm Presentation

Modelling and investigating the feasibility and logistics of multi-modal transport

Bryan Quadras

25 March 2024

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Introduction

Our last meeting

- The last milestone was the Proposal Review, where I presented my Research Plan and timeline.
- In my research plan, I defined four phases:
  - Setup
  - Capacity Analysis
  - Build/refine extended model
  - Logistics, analysis and recommendations
- At the Midterm Milestone, the phases Setup and Capacity Analysis are now complete.
- At the end of this presentation, next steps and a refined timeline will be presented.

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Introduction

What will be discussed today?

- Phase 1: Setup
  - Obtaining data (EC, GTFS)
  - Processing data (flight + train)
  - Choice of city pairs for analysis in Phase 2
- Phase 2: Capacity Analysis
  - Finding shortest path between cities
  - Analysing capacity through flights and trains
  - Investigating potential for shifts taking factors into consideration
  - Results from capacity analysis
- Next Steps

01

Phase 1: Setup

Obtaining/processing/tooling data

Obtaining and processing data

Flight/EUROCONTROL

- EUROCONTROL data on flight plans is used for flight data.
- Data is taken from the period of March 2019, the latest period available for research purposes. Specifically, top 100 airports by number of flights is selected.
- Airport info is generated. For each airport, its city, closest big city, country and country ISO code is used.
- Lastly, all flight pairs are generated and those that have connections are kept.

Relevant columns in EC FLIGHT data:

- ADEP (ICAO code dep airport) and LAT+LON
- ADES (ICAO code des airport) and LAT+LON
- AC Type
- FAT (Filed Arrival Time)
- AOBT (Actual Off-Block Time)
- AAT (Actual Arrival Time)

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Obtaining and processing data

Train/GTFS [1/4]

- For train route data, GTFS Schedule (General Transit Feed Specification) is used.
- This data comes from transit provider and contains specific information about stations, routes, trips, and services.
- Obtained data for many countries in Europe and for cross-regional transit services (e.g. Eurostar) from open sources (Mobility Database or directly from providers).
- Merging the files gives you the full picture - used for further processing.

Required dataset files in GTFS:

- agency.txt - agencies in dataset
- stops(_times).txt - stops/stations + times
- routes.txt - transit routes (part of a single service)
- trips.txt - trips (sequence of stops) for each route
- calendar(_dates).txt - service dates, and exceptions

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Obtaining and processing data

Train/GTFS [2/4]

- Processing of data is done in steps:
  - For every GTFS dataset, a day of services is chosen with either the most added services or least service exceptions.
  - For chosen services, all columns from routes, stops, stop_times and agency are merged, and appended to a data frame containing all the accumulated GTFS routes.
  - All routes are then processed through a function that converts all longitudes/latitudes into x, y coords using WGS84 projection, merges stops that are within 1 km, and assigns unified IDs and names to the merged stop. Also time calculations (duration, departure and arrival times) are assigned to the frame.
  - A directed network graph is created with all nodes (unified stops) and edges (individual routes between nodes) from the GTFS routes.
  - Finally, the final train routes between cities are compiled, using the graph and shortest path algorithm.

Obtaining and processing data

Train/GTFS [3/4]

no.	city_origin	city_destination	duration (mins)	distance (km)
275	Zürich	Nantes	530.0	1188.68
557	Cologne	Hamburg	225.0	381.96
947	Luxembourg City	Hanover	389.0	648.77
179	Munich	Bristol	614.0	1176.94
57	Amsterdam	Budapest	858.0	1196.4
818	Venice	Frankfurt	603.0	753.01
1198	Charleroi	Luxembourg City	102.0	117.22
1143	Belfast	London	616.0	523.07
925	Luxembourg City	Berlin	463.0	800.11
410	Geneva	Bordeaux	369.0	1000.97
1154	Aberdeen	London	383.0	693.66
995	Bristol	London	80.0	165.43
778	Marseille	Amsterdam	437.0	1116.51

Obtaining and processing data

Train/GTFS [4/4]

- For UK public transit: GTFS is now available for local bus services but not for trains.
- UK transit providers only provide data in TransXchange (TNDS) format.
- I used the open source UK2GTFS R package to generate GTFS data for UK trains in Great Britain.

- The final graph has about ~ 4800 nodes and $10M$ edges.
- This allows for routing between any stations in the regions considered in the GTFS data.
- Now that data has been obtained and processed, regions for city pairs for the further research need to be chosen.

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Choosing city pairs for analysis

- To choose city pairs for further analysis in Phase 2, different criteria were investigated:
  - Looking at cities with highest daily flights between them
  - Looking at cities within the same country with potential for a shift
  - Looking at cities which have moderate daily flights but potential to improve train infrastructure to increase shift possibilities
- Using the compiled flight data and train data, and finding matches between them, I concluded the following four city pairs that I would investigate further for Phase 2:
  - **Amsterdam – London**
  - **Paris – Toulouse**
  - **Berlin – Frankfurt**
  - **Copenhagen – Stockholm**

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02

Phase 2: Capacity Analysis

Analysing capacity and investigating shift feasibility

Finding shortest path between cities

Shortest Path Algorithm

- For analysis, finding shortest path between cities is important. Dijkstra's algorithm with custom constraints for time and transfer conditions were considered over built-in functions.
- The high level overview of the custom Dijkstra algorithm:
  - Transfer penalty and time penalties set, in order to disincentivise transfers and increase priority of departing closer to previous leg start time.
  - Starting from origin node, the neighbours of the node are explored. For every node that is not yet visited, the arrival time at current node is compared with the departure time of the neighbour and a final time measurement (including penalties) is computed.
  - This final time measurement and the node are added to a priority queue (heap queue), as long as it is the quickest time to reach that neighbour.
  - Once all neighbours are traversed, the node with the closest 'distance' is removed from the heap and the process begins again.
- With the algorithm, the shortest path can be found between any two nodes in the graph.

Capacity Analysis

Approach 1 [1/2]

- The aim is to analyse capacity and assess the extent to which shifts are possible from flights to trains, for the city pairs chosen in Phase 1.
- First, I look at measuring capacity of flights. From the processed data, used typecode and no. of daily flights in order to get a figure for no. of passengers. Utilisation of flights was assumed to be around 80%, I used OpenAP to get the flight seats in a 'high' configuration. All airport pairs at origin city and destination city were used in the calculation.
- Then, I look at measuring train capacity. For this, I load the node/edges graph and obtain the closest unified stop for the origin and destination cities. I find the shortest path between the two stops, and go through the edges used in the path.
- I then determine the maximum no. of passengers that can be taken through the whole route (for every edge, determine max. capacity using carriage type, number of carriages, and persons), and number of unique departure times throughout the day.
- Lastly, the percentage of passengers that can be shifted from flights to trains is computed.

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Capacity Analysis

Approach 1 [2/2]

There were some issues with this first approach...

- The routes I were getting with the shortest path algorithm were not yielding optimal routes (unnecessary delays and connections suggested).
- It would take a lot of time to load the graph of nodes/edges, due to its shear size. This formed as an obstacle for quick analysis.
- There was duplicate data for certain regional services which was at many times not in sync (slightly different departure times). This would cause unoptimal routes.
- Because of unoptimal routes being suggested, the number of departure times found was much less compared to expected values.

It was time for an iteration: a second approach!

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Capacity Analysis

Approach 2

For the second approach, I decided to change a few things to mitigate the issues I had with the first approach:

- Modify the shortest path algorithm to increase the transfer penalty to ensure that staying on the same trip (trip_id) is more favourable than changing train lines.
- Change how train data is processed to create subgraphs with data only from one or two providers (depending on the route chosen). For instance for Eurostar services, I would only choose Eurostar GTFS data, rather than also including Netherlands data, in order to avoid duplication/collision with NS International advertised routes (Amsterdam – London).
- Ensure that only services running on the most busiest day were considered, in order to mitigate that too few or too much departure times were considered.

These changes resulted in results that showed about a modest 30-50% shifting possibility for most city pairs, when considering current utilisation of train networks.

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Analysis Results

Amsterdam – London

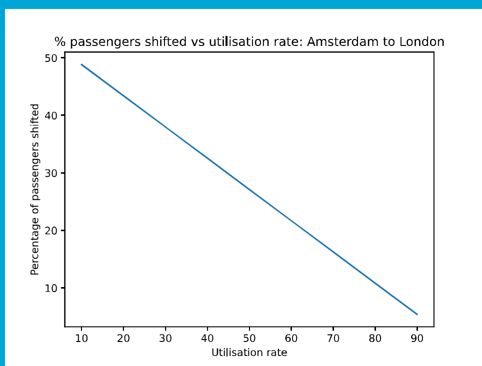
Flight:

- Shortest duration/distance: 53 mins/340 km
- Capacity per day: 8293 pax (54 flights)

Train:

- Shortest duration/distance: 269 mins/360 km
- Utilisation (assumed): 40%
- Adjusted capacity per day: 2700 pax (5 trips)

Shift: **32%** possible from flights to trains



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Analysis Results
Paris – Toulouse

Flight:

- Shortest duration/distance: 74 mins/625 km
- Capacity per day: 5791 pax (34 flights)

Train:

- Shortest duration/distance: 258 mins/587 km
- Utilisation (assumed): 55%
- Adjusted capacity per day: 2495 pax (11 trips)

Shift: **43%** possible from flights to trains

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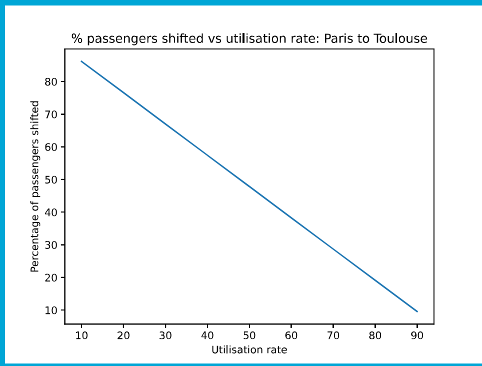

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Analysis Results
Berlin – Frankfurt

Flight:

- Shortest duration/distance: 59 mins/460 km
- Capacity per day: 5268 pax (25 flights)

Train:

- Shortest duration/distance: 260 mins/430 km
- Utilisation (assumed): 80%
- Adjusted capacity per day: 1656 pax (10 trips)

Shift: **31%** possible from flights to trains

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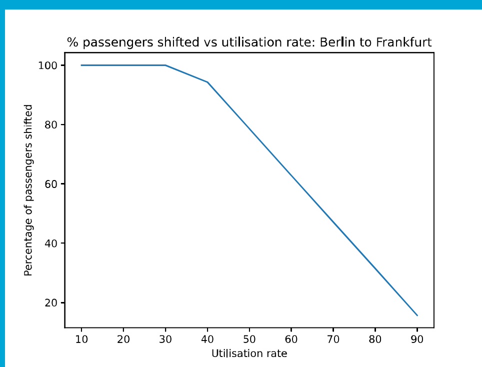

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Conclusions

Capacity Analysis

It can be seen that:

- For all three presented analyses results, a shift is feasible in the range of about 30% - 50%
- Especially for Paris – Toulouse and Berlin – Frankfurt, there is room to increase possible percentage of passengers that can be shifted if utilisation can be decreased (i.e. through infrastructure improvements allowing more people to travel through the network)
- For Amsterdam – London, the possibility of increasing shift percentage is more limited due to the current number of trips being 5 per day

Overall, the experiments done in this phase allowed for an investigation into capacity and shift feasibility for a diverse set of routes. This can now be easily extended to other routes for analysis, by applying the same techniques as have been done here.

03

Next Steps

Phase 3 and Phase 4

Next phases of research

Phase 3 and Phase 4

After the completion of Phase 1 and Phase 2 (as was defined in the Research Plan and first discussed during the Research Proposal Review), the next phases of research will commence.

- From the findings of the first two phases and my experiences thus far, I think it is wise to focus first on applying the next phases on research on the chosen city pairs and then later investigate any macro effects.
- Right now in **Week 17** of master thesis. The planning for the following phases is:
  - Week 17 – Week 20: Build and refine extended model with capacity and pricing factors
  - Week 21 – Week 25: Logistics, analysis and recommendations – including draft thesis deadline at end of Week 25 (May 24, 2024)
- Focus will be on building a model to investigate how change of pricing and capacity availability influence passenger choice, based on route/region.

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Thank you for your attention

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Modelling the feasibility and logistics of multi-modal transport

Greenlight Meeting

Bryan Quadras – 10 June 2024

TU Delft

A detailed look at the approach and its results

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Phase 1 – Air transport data

- Used research data from EUROCONTROL from March 2019 (latest data available without effect of COVID-19)
- Data source consists of flight plans submitted by airlines and other aircraft providers to EUROCONTROL's own "Network Manager"
- Sometimes, data has been updated by EUROCONTROL to include more accurate route path (based on radar observation)
- For this research, this provided 'open' data is seen as more than sufficient and accurate for a start at capacity analysis.
- Table describes crucial parameters taken for this setup phase

EUROCONTROL releases flight data for R&D purposes, subject to users agreeing the terms and conditions, which in summary are:

- **I shall use the ATM Dataset only for research & development**
- **I shall not share or distribute the ATM Dataset**
- **I shall duly acknowledge EUROCONTROL as the source of the ATM Dataset**
- **I am aware of and accept the fact that EUROCONTROL provides the ATM Dataset as-is, without warranties of any kind.**

Table 1: Relevant parameters of ECTL Research Flight Data used (adapted from [17])

Parameter	Description
ECTL_ID	A unique numeric identifier for each flight in the dataset
ADEP	ICAO airport code of departure airport of the flight
ADES	ICAO airport code of destination airport of the flight
Filed Arrival Time (FAT)	Time of arrival (in UTC) based on last filed flight plan
Actual Off-Block Time (AOBT)	The time that aircraft departs from its parking position.
Actual Arrival Time (AAT)	Time of arrival (in UTC) based on ATFM-updated flight plan
AC Type	ICAO aircraft type code
Actual Distance Flown [nm]	Distance flown in nautical miles

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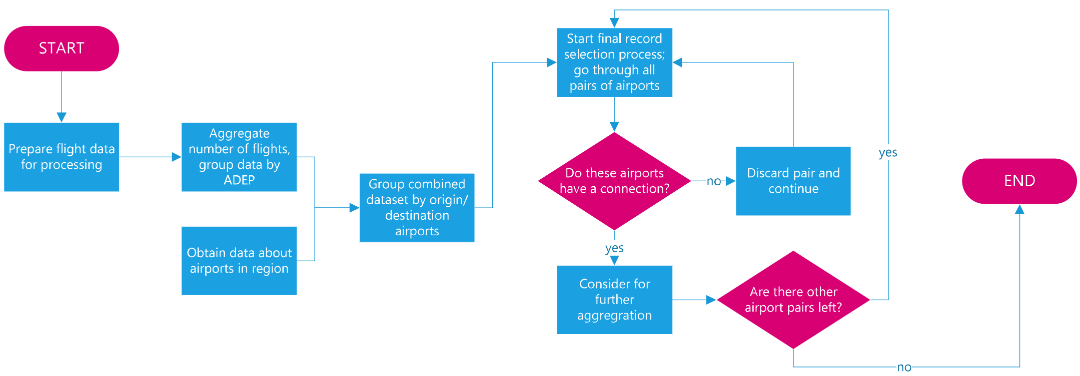
Phase 1 – Air transport data



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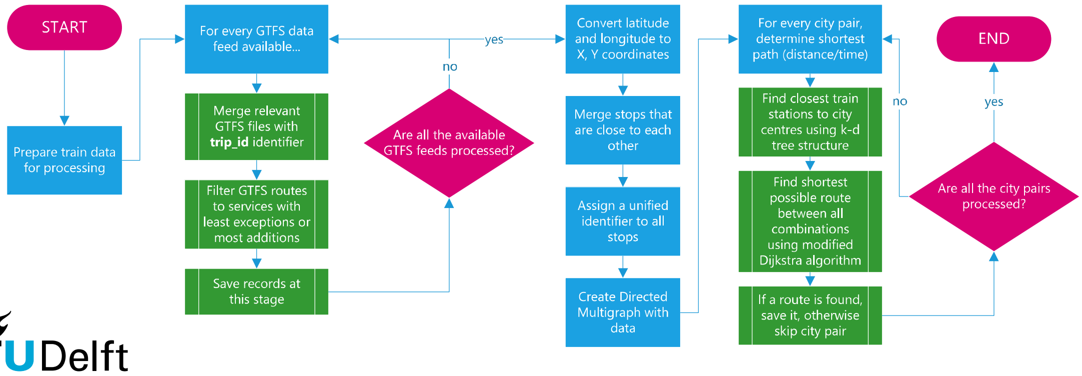
Phase 1 – Ground transport data

- Used GTFS Schedule data feeds.
- Available openly through transit providers and other open sources.
- Contained data on multiple forms of public transport, but focus was placed on train routes.



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Phase 1 – Ground transport data

no.	city_origin	city_destination	duration (mins)	distance (km)
275	Zürich	Nantes	530.0	1188.68
557	Cologne	Hamburg	225.0	381.96
947	Luxembourg City	Hanover	389.0	648.77
179	Munich	Bristol	614.0	1176.94
57	Amsterdam	Budapest	858.0	1196.4
818	Venice	Frankfurt	603.0	753.01
1198	Charleroi	Luxembourg City	102.0	117.22
1143	Belfast	London	616.0	523.07
925	Luxembourg City	Berlin	463.0	800.11
410	Geneva	Bordeaux	369.0	1000.97
1154	Aberdeen	London	383.0	693.66
995	Bristol	London	80.0	165.43
778	Marseille	Amsterdam	437.0	1116.51

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Phase 1 – Selection of city pairs

- To respect the constraints and limited resources of this project, a decision was made to choose three city pairs using specific criteria.
- When choosing the pairs, care was taken to choose city pairs for which results are likely to count significantly towards understanding the feasibility, logistics and large scale effects of shifting passengers.
- With this in mind, I decided to choose city pairs with a large amount of air traffic every day (number of flights per day) between them, and where all city pairs were in distinct regions.

Table 4: Top twenty unidirectional city pairs ranked by descending number of daily flights

Rank	Origin city	Destination city	Daily flights	Rank	Origin city	Destination city	Daily flights
1	**Amsterdam**	**London**	**54**	11	Nice	Paris	27
2	**London**	**Amsterdam**	**53**	12	London	Frankfurt	27
3	London	Edinburgh	43	13	Frankfurt	London	26
4	London	Geneva	43	14	London	Paris	25
5	Edinburgh	London	43	**15**	**Berlin**	**Frankfurt**	**25**
6	Geneva	London	43	**16**	**Frankfurt**	**Berlin**	**25**
7	**Paris**	**Toulouse**	**34**	17	Barcelona	Madrid	25
8	**Toulouse**	**Paris**	**33**	18	Munich	Berlin	25
9	Barcelona	London	31	19	Paris	London	25
10	Paris	Nice	28	20	Berlin	Munich	24

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Phase 2 – Capacity Analysis, Flight

- Philosophy with the analysis approach is to use as minimal variables as needed, to ensure that results are not skewed too heavily based on data sources.
- Capacity is measured as number of passengers that travel on flights between city pair in a day, taking an 'high' configuration as the main assumption.
- From the processed data, used type code and no. of daily flights in order to get a figure for no. of passengers. All airport pairs at origin city and destination city were used in the calculation, therefore the final figure is a weighted average of passengers.
- I used OpenAP to get the flight seats figure in a 'high' configuration.
- With this, the number of passengers that travel on the flights in total every day is determined. Information such as flight travel time and distance are also gathered using data from Phase 1.

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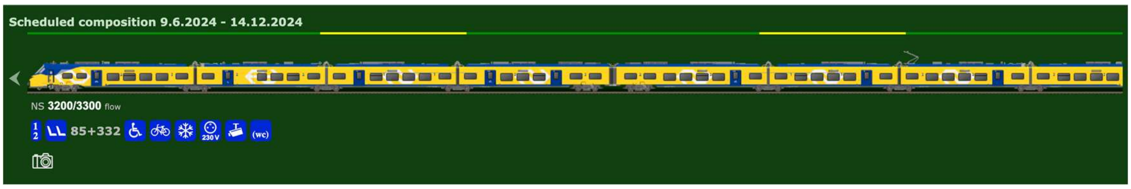
Phase 2 – Capacity Analysis, Train

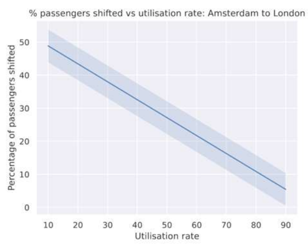
- I look at measuring train capacity. For this, I load the node/edges graph and obtain the closest unified stop for the origin and destination cities. I find the shortest path between the two stops, and go through the edges used in the path.
- I then determine the maximum no. of passengers that can be taken through the whole route (for every edge, determine max. capacity using carriage type, number of carriages, and persons), and number of unique departure times throughout the day.
- Data about number of carriages, carriage type and capacity is obtained from public sources such as vagonWEB. All other data is determined directly using subgraph from Phase 1.



Phase 2 – Capacity Analysis, Results

Table 6: Capacity analysis results for Amsterdam — London

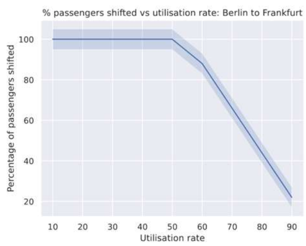
Amsterdam — London	Flight	Train
Travel distance	340 km	360 km
Travel time	53 min	269 min
Utilisation (assumed)	N/A	40%
Trips per day	54	5
(Adjusted) capacity per day	8293 pax	2700 pax



(a) Amsterdam to London

Table 7: Capacity analysis results for Berlin — Frankfurt

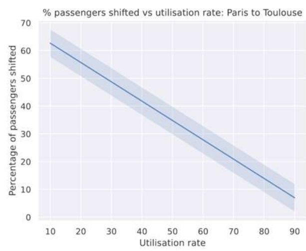
Berlin — Frankfurt	Flight	Train
Travel distance	460 km	430 km
Travel time	59 min	260 min
Utilisation (assumed)	N/A	80%
Trips per day	25	10
(Adjusted) capacity per day	5268 pax	1656 pax



(a) Berlin to Frankfurt

Table 8: Capacity analysis results for Paris — Toulouse

Paris — Toulouse	Flight	Train
Travel distance	625 km	587 km
Travel time	74 min	258 min
Utilisation (assumed)	N/A	55%
Trips per day	34	11
(Adjusted) capacity per day	5791 pax	2495 pax



(a) Paris — Toulouse

Phase 3 – Building the model (1/2)

- With the aim of the thesis being to find out how you can capture the effects of shifting passengers on environmental impact, passenger experience, total travel time and cost, I decided to make the model accept one important parameter.
- The main parameter into the model is percentage of passengers to be shifted for a given city pair.
- As output/indicators, we have the following:
  - Change in number of flights and trains that must travel to facilitate new situation after shift
  - Change in total carbon dioxide emissions across whole travel situation
  - Change in passenger experience, measured through change in total waiting time.

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Phase 3 – Building the model (2/2)

- How do we measure change in total waiting time?
  - By building an high level approximation for every component of time that builds up full trip from door-to-door (e.g. home in City A to home in City B)
- The intended effect is to provide an advantage to trips that consist of less 'time friction' as the total waiting time of passengers on those trips are significantly reduced.
- Instead of just comparing flight time to train time, total time can now be considered – a fairer comparison. For most time components, a low and high bound is taken to account for best and worst case scenarios.

Table 5: Time components that make up the total waiting time

Component	Description / full form	Implies
ADT	Time to arrive to terminal	Time to arrive to airport or train station
TTD	Total time to departure gate	Time taken for check-in / ticket check, passport control, security and boarding
TTO	Total time before take off	Waiting time until plane ready to take off or train ready to leave station
TAL	Total time after landing until end of taxiing	Waiting time until possible to leave aircraft or train
TTA	Total time until exit of terminal	Time for passport control, possible bag-pickup and customs
FIN	Time to arrive to final destination	Time to arrive to destination city centre region

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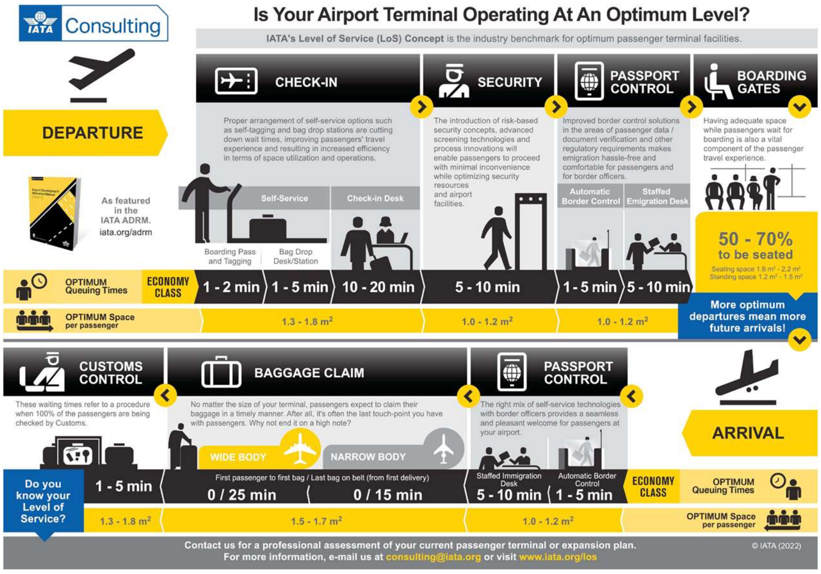


Phase 3 – Scenarios

To run simulations on this model that could be reasonably used in real-world practical applications, two scenarios were devised. Both scenarios are simulated to see the effects on two variables: change in total carbon dioxide emissions per passenger and change in average waiting time per passenger (both across all flights + trains).

Scenario 1:

Levying a tax on flight cost to the passenger based on distance travelled per flight.

Values will be varied from 0.05 EUR/km to 0.30 EUR/km.

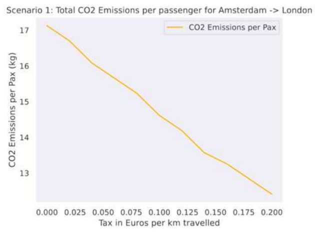
These values are ‘translated’ to percentage shifts for the model using research figure 0.489%/EUR of passengers no longer fly with increase in flight cost.

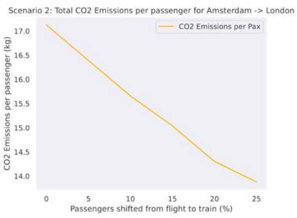
Scenario 2:

Investigating the effect of targeted advertising towards incentivising shifts on closed travel system.

Values of passenger shift will be varied from 5% to 25%.

Phase 3 – Results (selection)





- When looking at Scenario 1, it can be seen that an increase of 0.1 EUR/km of flight tax has the effect of reducing average waiting time by about 40-60 minutes across the board when considering all passengers.
- It can also be seen that, even though a large number of flights still remain after shifts, a decrease of 4-5 kg of carbon dioxide emissions per passenger across the board. This is about 40000 – 50000 kg decrease in total, which is significant.
- A similar trend is seen with Scenario 2, albeit with not as many slope changes. This can be explained due to the tax in first scenario resulting in much larger shifts than with marketing in second scenario.

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Phase 4 – Conclusion and Recommendations

- Overall, this thesis set out to investigate the feasibility and logistics of shifting passengers in a multi-modal transport system.
- It found that it is feasible at about 30 – 50% shifts possible in the three regions that were considered: Amsterdam – London, Berlin – Frankfurt and Paris – Toulouse.
- It also found that given different scenarios of levying tax or targeted marketing on passengers in this system can be successful, with respect to an increase in passenger experience due to decrease in average waiting time per passenger. Also better on the environmental with a reduction of 4 – 5 kg of carbon dioxide emissions per passenger.
- In the short-term, no major infrastructure development is needed. The only hurdle in transit provider perspective is dealing with increasing train services to handle capacity from shifts and planning/scheduling.
- There is also the question of whether airlines and ground transport providers may work together given it may result in less air travellers, but this is the wrong perspective to take in my opinion. It is better to look at how the passenger experience improves for the passengers who still go on flights and subsequently the passengers who also enjoy a better passenger experience on the train. It relieves the global airport systems of pressure, while shifting that pressure onto the train system which as was seen can handle the extra capacity trivially in comparison.
- For future studies, focusing on a specific region and diving deep into comparing whether a shared multi-modal flight and train approach works better or a flight ban approach for short-haul flights is a recommendation.

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