Crossing Europe asleep, not aloft

Modelling night train demand potential for maximum air-rail substitution

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TU Delft

SWECO

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by

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Preface

Before you lies the final product of my master thesis project. A project that was intended to take nine months but ended up lasting for sixteen, thanks to a range of various family-related and personal circumstances all occurring simultaneously. A project on a topic that had been stuck in my head for years, which I had never expected could be suitable for a master thesis until Niels proposed the exact same topic by himself during an orientating talk in the spring of 2023. A topic close to my heart, from my lifelong passion for improving (international) rail transport and for protecting the fragile environment we live in.

I would like to express my gratitude to my committee for all of their feedback, advice, support and patience throughout my project, especially during the difficult circumstances that seriously impeded and even halted my progress on several occasions. Niels, thank you especially for alerting me of pushing myself too far when I did, as well as helping me stay focused and prioritise. Nejc, thank you especially for sharing your deep knowledge on travel behaviour and helping me find my way through the literature. Rob, thank you especially for your valuable constructive feedback and for paying attention to my health.

On the side of Sweco Nederland: Lucia, thank you especially for our personal talks and for sharing your own valuable thesis experiences. Gijs, thank you especially for your sharp views and your technical knowledge on international rail barriers. And finally, thanks to my colleagues of the Railstudies and Railverkeerstechniek teams for their warm welcome, their tips, opinions and insights, their compassion during my times of struggle, the pleasant talks and walks we shared at the office, and of course the monthly tabletop game events.

All that remains to me is to wish you a pleasant read.

D.S. Dietzenbacher
Utrecht, August 2024

The cover picture was taken by the author from the rear of the Berlin-Stockholm night train on July 19th, 2022.

The author declares no conflicts of interest.

Summary

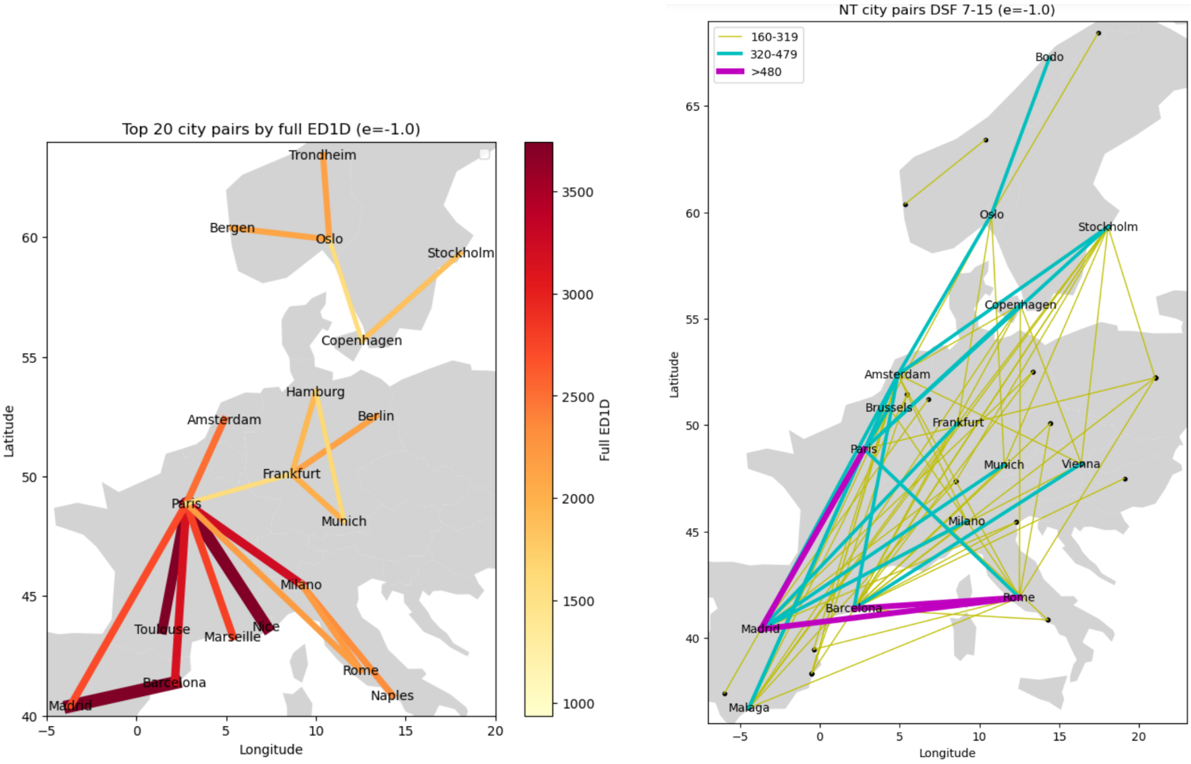
Air travel's greenhouse gas emissions contribute to harmful environmental effects more strongly than other modes relative to its share in the modal split, and they are the fastest-growing source of EU emissions. This natural record growth will see emissions multiply in a few decades, and currently introduced or projected policies, innovations and optimisations are by far insufficient to reduce these emissions substantially; a strong reduction of air travel is required to achieve climate targets. Passenger rail is more sustainable by emissions, and considering the significant share of passengers travelling distances up to 1000 km, air-rail substitution has potential to contribute to a solution to aviation's emissions. Earlier studies into air-rail substitution showed high potential but noted that passenger rail in its current state is unable to meet requirements to fulfill this substitution, especially struggling to be competitive on longer distances; however, night trains can provide an alternative here due to different perception of travel time: travel time spent sleeping is experienced to be shorter.

International daytime trains have been the subject of various academic studies and cooperation between railway sector parties. However, night trains have received less attention: earlier publications regarding the development of European night train networks have not (publicly) included an academic study and used different approaches to propose routes, or focused on tourist trips specifically. Furthermore, existing air-rail substitution studies assumed air travel would only be reduced when and where rail is equally or more competitive compared to air, even though this approach has been proven insufficient to reach significant emission reductions. This thesis turns the question around: instead of only reducing air travel when the rail product is better, remove flights first and investigate the effect on rail demand. This thesis thus aims to discover the additional (night) train demand that would result from replacing flights in Europe. The formal research question is as follows: **On what routes in the continental Schengen area would night trains be required to enable maximum substitution of air travel?**

The spatial scope of the case study used for this thesis is restricted to the part of the Schengen area connected as a fixed link to the mainland European rail network by standard gauge. Rail travel time calculation will not consider the effects of track works, carriage exchanges and future developments in railway infrastructure; night trains are assumed to have approximately the same travel time as daytime trains. Demand estimation will not consider transfer passengers on flights (instead assuming all passengers on a flight have that flight leg as their entire journey), pricing, booking, reliability, carriage characteristics and comfort. Legal, regulatory, political and societal factors remain out of scope too. Following literature review, the influence of other modes (such as the car) is kept out of scope in the modelling approach as well.

In order to answer the research question, a gravity model is applied: double the travel time (when substituting air with rail) means half the travellers remain. A railway routing tool is used to estimate rail travel times between cities, with 20% buffer time applied and time supplements for both access/egress and airport idle time added. Passenger numbers are retrieved from a Eurostat dataset of flight passenger counts on each air route. For determining which share of the remaining travellers will seek to travel by night train (rather than daytime train), the assumption is made that the share of night train demand as part of the full demand increases linearly from 7 to 15 hours of rail travel time, with zero demand for the night train below 7 hours and 100% demand for the night train above 15 hours. Such an assumption on the night train's demand share is named a ”Demand Share Function”.

A total 237,000 daily passengers each way are estimated as full demand (for daytime and night train travel combined) from air-rail substitution, meaning 1 in 3 current air passengers would choose to not travel or travel elsewhere. Of all cities, Paris is the strongest generator of full demand, good for 43,000 daily passengers each way in all directions combined, followed by Frankfurt and Barcelona. The top twenty most popular city pairs by full demand are shown in Figure 1a. Aggregated by country, the four most popular country-to-country relations concern domestic travel, within France, Italy, Germany and Norway; the most popular international relation is France-Spain. Satisfying the full demand is roughly estimated to require 219,000 additional seats on the network, equivalent to several hundreds of high-



(a) Top 20 city pairs by estimated full demand from maximum air-rail substitution. Line colour and thickness represent the size of this estimated demand: the darker and thicker the line, the higher the demand.

(b) City pairs where estimated daily one-way night train demand exceeds 160 passengers, which is 50% of the capacity of a new Nightjet trainset (or all of its sleeping berths).

Figure 1: Maps of key routes for estimated full and night train demand.

speed trainsets (500 ICE 3 Neo or 400 TGV Duplex sets) or a few thousand carriages (2,700 carriages if the capacity is 80 passengers).

Daily one-way night train demand from air-rail substitution is estimated at 47,000, or 20% of full estimated rail demand, equivalent to circa 300 new Nightjet trainsets (with a capacity of 320 passengers each) or a few thousand classic carriages. Madrid-Rome and Barcelona-Rome are the city pairs with highest night train demand, and nine of the top ten city pairs are to/from Spain. Of all cities, Madrid has the highest night train demand in all directions combined (6,000 daily each way), followed by Amsterdam and Barcelona. When aggregated by country as shown in Figure 2, Spain has the highest night train demand as origin/destination (estimated at a total of 68 Nightjets each way per night), followed by Italy and Germany; Spain-Italy is the country relation with highest night train demand, followed by Spain-Germany and Spain-Netherlands. Generally, most city pairs with high night train demand are oriented northeast-to-southwest, as can be seen from Figure 1b.

Changing the value of travel time elasticity (the degree to which a change in travel time influences passenger numbers) has a linear effect, with a 15.8% higher demand observed under a value of -0.65 (meaning a doubling of travel time decreases passenger numbers by only 32.5%) compared to the baseline -1.0. Different Demand Share Functions, describing the modal share of night train in total estimated substitution demand depending on travel time, are tested as well. Such Demand Share Functions where the range of mixed daytime/nighttime travel demand is wider (but centred around the same midpoint of a 50/50 split at 11 hours of travel time) generally estimate higher night train demand. The Demand Share Function from 4 to 18 hours (based on the shortest currently existing night train connection, Malmö-Stockholm) has a 23.9% higher night train demand estimate (59,000) than the baseline 7 to 15 hours, and highlights increased shorter-distance night travel demand, especially for domestic overnight travel in, e.g., Norway.

The following policy recommendations are formulated for the further development and improvement of night train services in Europe:

- to focus primarily on connections to/from Spain (and secondarily Italy);

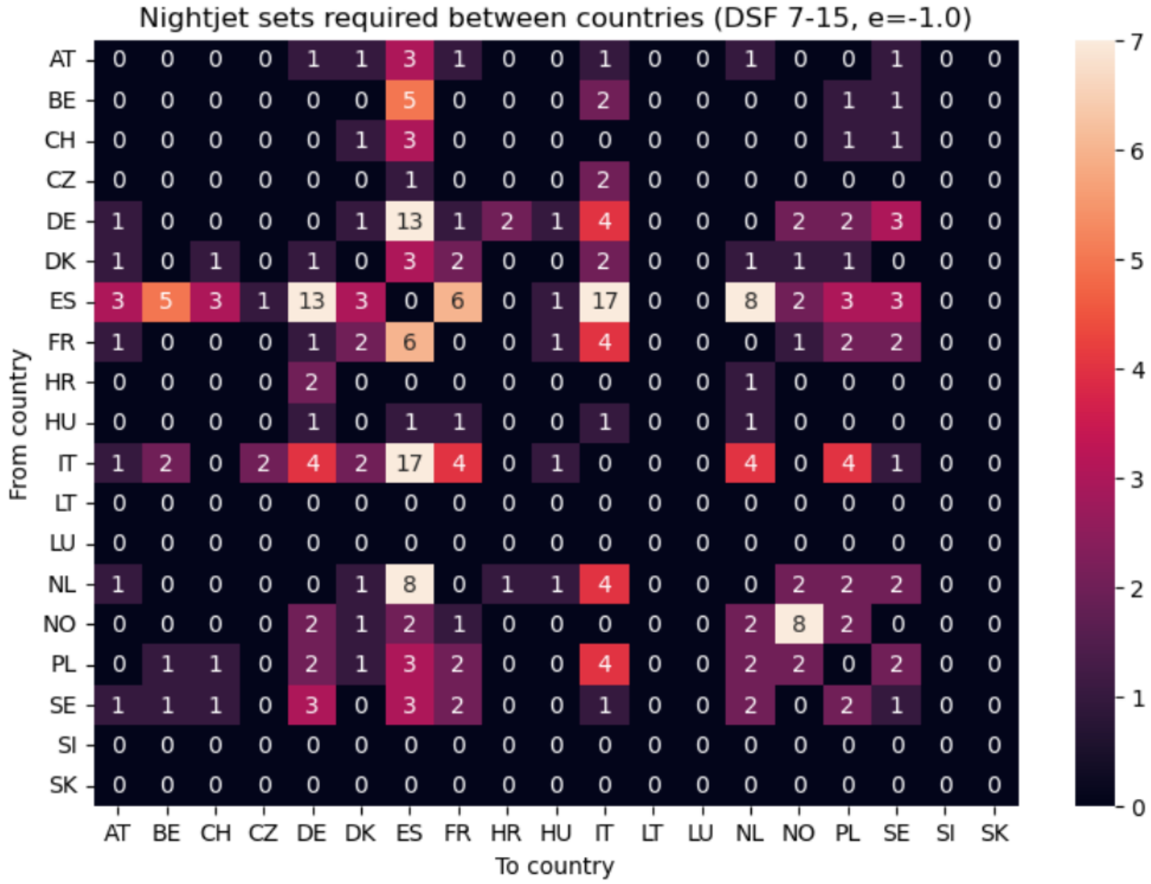


Figure 2: Number of new Nightjet trainsets (capacity 320) required to fill the aggregated daily night train demand each way between countries.

- to work on the resolution of border barriers for long-distance (night) rail transport;
- to improve the position of and attention for night train transport in western European countries;
- and to focus on the introduction of northeast-to-southwest-oriented night train connections.

The research may be continued by, for example, using city pair demand estimations to form night train routes with stopping patterns and timetables. The methodology may be applied to different case studies, such as ones only using data for specific seasons within a year (rather than full-year averages). The results can be used to formulate policy recommendations such as those described above, and to develop a general idea of the scale of potential demand for night train rolling stock in a scenario of large-scale air-rail substitution, useful for the acquisition and development of new rolling stock.

However, there exists a significant literature gap in the field of long-distance and night train travel behaviour, especially for scenarios where air travel is substituted at a large scale and/or excluded as an option. Primarily this literature gap, as well as time and resource constraints in this thesis, have required the use of several assumptions that showed a strong effect on the quantitative outcome when associated input parameter values were altered. Main limitations include the exclusion of cars and other modes in the model, the exclusion of pricing as a factor, the choice for fixed time supplements (instead of location-specific supplements) for airport/station access and egress times, the lack of distinction between point-to-point and transfer passengers on flights, and the absence of a method to verify the results. Further research is suggested into travel behaviour under the maximum air-rail substitution scenario discussed here, into location-specific access/egress and idle times at stations and airports, to make the step from city-to-city demand estimations to the formation of proposed night train routes and timetables, into destination changes and interactions with other modes, into seasonality of long-distance travel demand, and into the actual effect on greenhouse gas emissions if this scenario is

implemented. All in all, this thesis provides an indication of the most interesting regions and corridors to further explore, and simultaneously points out the need for additional academic research to gain a full understanding of the exact scale of rail investments required to facilitate large-scale air-rail substitution.

Contents

1

Introduction

1.1. Context

Despite long-distance trips (above 100 km) only taking up a very small share of total passenger trips, they amount to a far larger share of greenhouse gas emissions of passenger transport (Geržinič et al., 2024); 1-1.5% and 50% respectively for the Netherlands and Flanders (van Goeverden, 2015). One of the key modes in long-distance travel is aviation, which produces greenhouse gas emissions contributing to harmful anthropogenic global warming (Terrenoire et al., 2019). In 2022, aviation accounted for 4% of total EU greenhouse gas emissions, and circa 13% of transport emissions (European Parliament, 2022). This was despite having a mere 7.3% modal share in passenger transport - with 976 million passengers annually (Eurostat, 2024a) - and 0.2% in freight transport (Eurostat, 2023b), making it an above-average polluting mode. Aviation is the fastest growing source of all EU emissions, having a record 146% growth compared to 1990 and projected to continue increasing even after the COVID-19 pandemic (European Parliament, 2022).

Worldwide emissions from international aviation alone have recovered to their pre-pandemic level of 600 Mt CO2 and are projected to rise to 1600 Mt by 2050 without structural improvements (ICAO, 2024). Even though emission reduction policies are in place and/or being introduced, technological innovations are ongoing and potential exists for optimisation in air traffic management, these improvements are by far insufficient to reduce these emissions substantially to the level required by climate targets (Åkerman et al., 2021; Larsson et al., 2019). Maximum deployment of technological improvements and optimisation of air traffic management and infrastructure use would only reduce global international aviation emissions from 1600 Mt to 1150 Mt (ICAO, 2024). This is mainly due to record growth of air traffic, both for passengers and freight, and a long history of exemption from emission reduction policies (European Parliament, 2022). A significant reduction of air travel is required to achieve these targets, in the order of double-digit percentages (Åkerman et al., 2021).

For EU countries, a large share of these air travel emissions is generated on short and medium-haul passenger routes up to 1000 km (Alonso et al., 2014). In 2022, 12% of all European air passengers (amounting to 100 million passengers) travelled distances below 500 km, while a total of 35% of passengers (or 288 million) flew less than 1000 km (Eurostat, 2023a). Scheduled commercial passenger flights can be as short as 188 km for Frankfurt-Dusseldorf (FlightsFrom.com, n.d.) despite the existence of a parallel rail connection taking merely 70 minutes (Direkt Bahn Guru, n.d.).

In terms of greenhouse gas emissions, passenger rail travel is a significantly more sustainable mode than air (and road) (Boschmans et al., 2021; European Environment Agency, 2021). In 2022, rail only contributed to 0.1% of total EU emissions despite a 5.6% modal share in passenger transport and 5.5% in freight transport (Eurostat, 2023b). Passenger rail therefore has potential to reduce pollution and energy consumption through a shift from air (and road) to rail travel (Jehanno et al., 2011). However, despite its promising position, European passenger rail suffers from a variety of problems, inefficiencies and barriers, such as non-increasing (or even decreasing) seat capacity (Fraszczyk et al., 2016) and international service offer, lack of European coordination and information provision (Witlox et al., 2022). In Central Europe, trends have shown that (decreases in) travel times are not so much dependent on new infrastructure as on improvement of contextual and (geo)political circumstances (Seidenglanz et al., 2021).

Earlier studies have investigated the potential for this substitution, calculating how many passengers can be tempted to change from air to daytime (and sometimes high-speed) rail in a competitive environment between the two modes (e.g.: Bergantino and Madio, 2020; Savelberg and De Lange, 2018; Durand and Romijn, 2023). For Amsterdam airport, for example, a potential 1.9 to 3.7 million annual journeys could be substituted given feasible reductions of rail travel times, increased frequencies, the resolution of transfer inconveniences and the reduction of ticket fares (Kroes and Savelberg, 2019). Although considerable potential for substitution exists on shorter routes (measured by overland distance) (Savelberg and De Lange, 2018; Durand and Romijn, 2023), rail as a mode is currently inferior to other modes for the majority of long-distance journeys measured by distance and emissions (van Goeverden et al., 2019). Rail frequently loses the competition with air on longer routes due to the longer distance covered and the lower average speed, even when taking into account access and egress times as well as security and check-in formalities for airports (Savelberg and De Lange, 2018; Durand and Romijn, 2023). Night trains can provide an alternative here, since (part of) the travel time is spent sleeping and thus the experienced travel time for the passenger is shorter (Heufke Kantelaar, 2019).

1.2. Research gaps

Several research gaps become apparent when reviewing existing literature. The main gaps which this study will attempt to address are described in this section; other gaps relevant to the topic will be described in Chapter 2.

There have been several proposals from pro-rail groups (e.g.: Oui au train de nuit, 2020) and governments (e.g.: Bundesministerium für Verkehr und digitale Infrastruktur, 2020) alike into comprehensive networks of night trains for parts of Europe. However, these were not (publicly) accompanied by an academic study to defend the choices for the presented routes based on objective metrics such as demand forecasts. In fact, in one particular case the chosen approach was to propose routes based on the explicit objective of improving connections to more distant parts of the country, regardless of whether a large (potential) demand exists on each route (Direction générale des infrastructures, des transports et de la mer, 2021). One thesis models demand potential for night trains as an alternative to air travel (Odendahl, 2020), although this is geared towards substitution of tourist trips specifically and is not a general approach for all types of trips.

This forms a contrast with the situation for daytime trains, including high-speed trains. These have received more attention in scientific literature, modelling potential demand for European passenger rail (Donners, 2016) or connectivity between long-distance trains and short-haul flights (Bruno, 2022). The topic has been addressed by railway sector parties as well, such as a cooperation of several rail infrastructure managers developing a coherent design of international passenger rail services on expected infrastructure under the 'Eurolink' umbrella (Wesdorp and Moerman, 2021).

Secondly, the aforementioned studies into air-rail substitution that were found all assumed that flights would only be substituted if the proposed rail product was competitive enough to draw passengers away from air travel. This is in spite of the finding that only executing air-rail substitution on routes where rail is currently competitive would only yield limited emission reductions (van Goeverden et al., 2019). No (hypothetical) study was found that assumed air travel to be removed entirely - or as much as reasonably possible - within an area regardless or ahead of the offered alternative train product. In other words, instead of attempting to increase the competitive position of rail, the competitiveness problem would be solved instead by removing air travel from the competition.

1.3. Research questions

This thesis intends to explore both research gaps identified above in a combined topic: an academic study to predict the upper limit of night train demand potential in a hypothetical situation in which air travel within the scope area is no longer available as an option entirely. The purpose of this thesis is to provide an idea of the overall scale of night train demand that would arise from maximum air-rail substitution, rather than generate a list or network of specific routes. This thesis is intended as a contribution of academic knowledge on an air-rail substitution scenario that has not yet been explored, providing insight into the effects and scale of air-rail substitution in this scenario with the aim of reducing the emissions of harmful greenhouse gases. The hypothetical scenario at hand can be relevant to policy makers and (debates on) governance, serving as a factual argument in discussions on stronger restrictions of passenger air travel with regard to emission reductions. The eventual results of this thesis may also prove their worth as a guideline for policy makers regarding night train rolling stock schemes and night train-promoting policies.

In order to address the research gap identified above, the main research question of this thesis is as follows: **On what routes in the continental Schengen area would night trains be required to enable maximum substitution of air travel?**

In order to appropriately design a research plan to answer this question, it will be divided into the following smaller, more practical sub-questions (RQs), shown here with a brief explanation on their content:

1. *What is the expected maximum demand for rail travel between city pairs from air-rail substitution?*
   It is assumed that night trains are only to be introduced between cities with sufficient demand to fill the train, requiring an estimation of demand generated by air-rail substitution.

2. *What is the expected maximum demand for night trains between city pairs from air-rail substitution?*
   Following the estimation of total rail demand from air-rail substitution, it must be determined what share of this demand would actually concern night train demand (as opposed to demand for daytime travel).

3. *What are the performance and operational implications of the resulting demand estimation?*
   The demand resulting from RQ1 and RQ2 is to be compared and assessed. City pair demand can be used to give insight in possible routes for night trains. The total demand and number of recommended services give an idea of the amount of rolling stock that would be required to operate such a network, which may be of use to policy makers to determine the scale of investment needed to execute the scenario of maximum air-rail substitution. Furthermore, comparisons with existing night trains can give pointers to existing barriers or potential flaws in the model.

4. *What variables have influence on the demand estimation results and to what extent?*
   The results from the above research questions are dependent on several factors. For instance, what travel behaviour is expected when air travel is substituted? How much travel time is still considered ”acceptable” for a night train? When is demand considered to be ”sufficient” for a night train? Are there different methods (or additional variables to include) to estimate the demand for these potential new night trains? This research question intends to provide insight into the meaning of the theoretical findings: if a parameter or variable were to be changed or added, including factors kept out of scope, what would be the expected effect on the outcome?

1.4. Scope

In order to make this research topic feasible to complete within a master thesis project, the complexity of the research must be reduced to an appropriate level. This section describes the design choices made for this project, along with a reasoning for these choices.

1.4.1. Spatial scope

As partially implied by the formulation of the main research question, the spatial scope of this research is limited to cities that are:

- within the Schengen area (in order to avoid time supplements and potential demand effects of border checks);
- connected by fixed rail link to the European mainland (in order to avoid time supplements related to maritime transfers);
- reachable via tracks with the European standard railway gauge of 1,435 mm (in order to avoid additional travel time or logistical restrictions due to gauge-changing operations or resulting additional transfers).

1.4.2. Rail travel times

The following factors that may be of relevance in reality to the calculation of rail travel times (potentially relevant to demand estimation in RQ1) or the process of forming night train routes (RQ3) are kept out of scope in order to adhere to time and resource limitations:

- **Track works.** Overnight track works may impact the travel time of a night train through delays or detours. Unless these works are long-term of nature (i.e., last one or multiple years), these works are disregarded.
- **Carriage exchanges.** Some existing night trains are composed of two or more portions of carriages with different destinations, with the exchange of carriages between trains occurring at intermediate stations. However, only night trains with a fixed composition throughout the journey and therefore no en-route shunting are considered for now.
- **Future developments in railway infrastructure.** This research is executed based on the current state (in 2024) of the rail network within the scope area. The future opening or closure of tracks and lines, as well as upgrades or downgrades in local line speeds are disregarded, whether they are already under construction or still under consideration.

1.4.3. Demand estimation

In the process of estimating expected demand for night trains from air-rail substitution (relevant to RQ1), the following factors are to be kept out of scope:

- **Transfer passengers on flights.** It is assumed that all recorded passengers between airport pairs are travelling from the city of the first airport to the city of the second airport. The main reason for this decision is that little data is (publicly) available regarding the split between origin-destination and transfer flows (Maertens et al., 2020; Maertens and Grimme, 2015). Where such data is found or compiled, it is either aggregated at the airport level (as opposed to the route level) or disseminated with altered numbers to uphold confidentiality (Durand and Romijn, 2023). Attempting to accurately model different circumstances for transfer and origin-destination passengers in this study would thus require additional assumptions and/or the use of aggregated and/or incorrect data. Additionally, not all city-to-city demand is covered by passenger numbers on direct flights. The effect of transfer passengers on a flight between two cities in the scope area described above is thus compensated somewhat by passengers flying indirectly between those two cities with a transfer elsewhere.
- **Pricing, booking and reliability.** The influence of pricing incentives and travel costs on demand will not be addressed; determining appropriate pricing for a night train is not part of the scope, and the current demand is taken as the baseline. The same holds true for the booking system: it is assumed that tickets for the night train can be booked easily on a well-functioning platform. Furthermore, it is assumed that the railway systems functions sufficiently reliably and adaptive to disruptions to be an acceptable mode of transport for long-distance travel for all.
- **Carriage characteristics and comfort.** Night trains may consist of different types of accommodation in terms of comfort level, amenities and privacy. Different accommodation types can attract different passengers. This research does not discern between different types of comfort categories on night trains. The entire passenger capacity of a night train is included and its comfort categories are generally considered equal. It must be noted that this report uses the term ”night train” to refer to overnight trains with sleeping accommodation provided for passengers. This must not be confused with seat-only trains running during the night, which are disregarded in this research.

1.4.4. Broader context

Finally, **legal, regulatory, political and societal factors** will not be considered in this research either. Developing a legal or regulatory framework for implementing new night trains and/or disallowing passenger air travel is not part of the scope. It is assumed that the situation of (a need for implementation of) maximum air-rail substitution is achieved, without describing the legal, governance or societal context that is or may be required to achieve this in further detail than mentioned in Section 1.2.

1.5. Report structure

The remainder of this report is structured as follows:

Chapter 2 analyses relevant literature regarding this topic and/or describing potential methods to answer the research questions. Chapter 3 outlines the methodology and datasets used in this research, and describes the case study. Chapter 4 shows and interprets the results. Chapter 5 discusses the implications of these results and describes their limitations. Chapter 6 contains the conclusion of this report, providing answers to the research questions, formulating policy recommendations, and providing suggestions for further research. As appendices are included: the bibliography, several tables used or generated during research, and the code used to generate the results.

1.6. Summary of introduction

Aviation's greenhouse gas emissions contribute to harmful environmental effects more strongly than other modes relative to modal share, and are the fastest-growing source of EU emissions. This natural record growth will see emissions multiply in a few decades and currently introduced or projected policies, innovations and optimisations are by far insufficient to reduce these emissions substantially; a strong reduction of air travel is required to achieve climate targets. Passenger rail is more sustainable by emissions, and considering the significant share of passengers travelling distances up to 1000 km, air-rail substitution has potential to contribute to a solution to aviation's emissions, yet various barriers and inefficiencies hamper the competitive position of European passenger rail. Earlier studies into air-rail substitution showed high potential but noted that passenger rail in its current state is unable to meet requirements to fulfill this substitution, especially struggling to be competitive on longer distances; however, night trains can provide an alternative here due to different perception of travel time.

International daytime trains have been the subject of various academic studies and cooperation between railway sector parties. However, night trains have received less attention: earlier publications regarding the development of European night train networks have not (publicly) included an academic study and used different approaches to propose routes, or focused on tourist trips specifically. Furthermore, existing air-rail substitution studies assumed air travel would only be reduced when and where rail is currently competitive enough, even though this approach has been proven insufficient to reach significant emission reductions. No study was found that assumed removal of air travel regardless of the competitive position of rail, even though such a scenario can be relevant for both emission reduction policy and discussions and rail management policy.

Using four research questions, this thesis will investigate the scale of potential night train demand in the continental Schengen area in the hypothetical scenario of replacement of all passenger flights within the area. This contributes to academic knowledge on an unexplored air-rail substitution scenario with the aim of reducing the emissions of harmful greenhouse gases. The scenario is relevant for policy and governance on both air travel restrictions for greenhouse gas reduction and night train rolling stock investments and policies.

The spatial scope of this thesis is restricted to the part of the Schengen area connected as a fixed link to the mainland European rail network by standard gauge. Rail travel time calculation will not consider the effects of track works, carriage exchanges and future developments in railway infrastructure. Demand estimation will not consider transfer passengers on flights (assuming all passengers on a flight have that flight leg as their entire journey), pricing, booking, reliability, carriage characteristics and comfort. Legal, regulatory, political and societal factors remain out of scope as well.

2 Literature review

This chapter provides a review of academic literature especially relevant to the topics of long-distance travel, night trains and air-rail substitution. This is intended to serve as a method to determine the research questions are relevant and sound, to give an overview of existing research on the topics the research questions concern, and to provide inspiration for the development of a research plan to accurately answer the research questions.

The literature review is performed primarily using Google Scholar (Google, n.d.-b), using (combinations of) keywords such as the following:

- access egress;
- European transport/travel;
- (international) (passenger) rail;
- long distance travel (behaviour);
- maximum day travel time;
- mode share;
- night train;
- value of time.

Further sources used include the repository of Delft University of Technology (Delft University of Technology, n.d.), specific literature and authors recommended by supervisors and colleagues, and key authors and literature cited by initially found literature.

2.1. Long-distance travel

This section describes literature concerning the characteristics and behaviour of long-distance rail travel and travellers, relevant to RQ1 and RQ2.

2.1.1. Value of time

In a survey research on COVID-19 risk perception in long-distance travel by rail, air and road on a non-representative sample of 705 Dutch travellers, Geržinič et al. (2024) identified four traveller segments based on their behaviour and willingness to pay for several travel characteristics. These are shown in Table 2.1. The overall sample average willingness to pay for travel time was 40€/h.

A literature review by Weisshaar (2024) identified travel time as a crucial factor in long-distance traveller decision-making. In order to show the effect of infrastructure quality on modal split, Geržinič et al. (2024) used mode-specific speed averages and idle times to determine travel time and cost through linear functions, varying the average rail speed between 70 and 300 km/h. Distance-based travel costs were estimated using a long-distance travel pricing dataset (Tanner and Provoost, 2023).

Segment name	Share	Willingness to pay (travel time)	Main preferences	Main characteristics
Time-sensitive travellers	30%	72€/h	Insensitive to comfort Strong train preference Strong car aversion	Low car ownership Representative income, education & gender Lower trip frequency Mostly business travel
Prudent travellers	36%	50€/h (1st class: +14€/h)	Car preference on shorter trips Plane preference on longer trips	Younger Predominantly male Higher trip frequency
Frequent train-loving travellers	15%	38€/h (1st class: +20€/h)	Strong train preference Plane and car aversion Accepting far longer travel time for rail than air	Lowest car ownership Older & highest education Predominantly female Highest trip frequency
Cautious car travellers	19%	15€/h	Insensitive to comfort Strong car preference	Highest car ownership

Table 2.1: Summary of the demand segments for long-distance travel identified by Geržinič et al. (2024). Specific COVID-19-related attributes are omitted.

These functions are shown in Figure 2.1. The night train was not included in Geržinič et al. (2024)'s work, but Heufke Kantelaar (2019) found that the value of night train travel time is lower than that of a morning airplane.

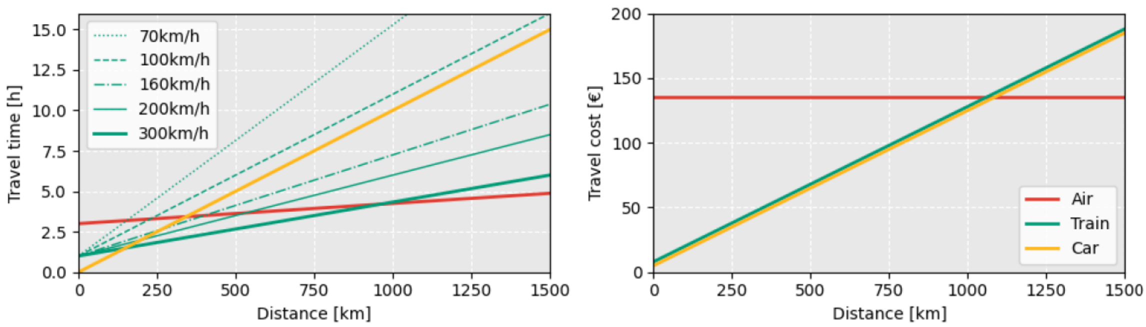


Figure 2.1: Functions for mode-specific travel times and costs (Geržinič et al., 2024).

In existing long-distance travel behaviour surveys regarding high-speed rail, in-vehicle time was found to have a value of time in the range of 10-30€/h, while access/egress to/from the station was valued at 20-50€/h, as reviewed by Geržinič et al. (2024). Generally, these surveys have shown strongly diverging and inconsistent results regarding the effects and values of attributes such as frequencies, waiting time, punctuality and comfort; however, it was noted that these values could not reliably be approximated using short-distance (commuter) travel behaviour studies due to a fundamental difference in perception of these attributes in long-distance travel (Geržinič et al., 2024).

2.1.2. Travel time elasticity

Elasticity is a measure of the effect of a change in one variable on another. When taking two variables, A and B, the A elasticity of B expresses how strongly an increase/decrease in A affects B. As an example, if the travel time elasticity of demand is -0.5, a 10% decrease in travel time causes a 5% increase in demand.

The travel time elasticity of demand can be a good contributor to estimations of travel demand in changing conditions. Over the past decades, multiple studies have found varying values of this elasticity in various scenarios. A meta-study (Wardman, 2012) summarised several hundreds of these studies and found the following elasticity values that may be relevant to this research:

- -0.69 for train travel (as opposed to car and bus), across 116 studies;
- -0.65 for inter-urban travel (as opposed to urban travel), across 128 studies.

Börjesson (2014) investigated elasticities and cross-elasticities specifically for the case of air-rail substitution, with a focus on cases of newly constructed high-speed lines affecting travel behaviour. Börjesson found a wide range of demand elasticities, highlighting a value of -1.0 for air demand in response to rail travel time reduction upon the introduction of high-speed rail service on the corridor between Stockholm and Göteborg. Börjesson noted that reliable values for cross-elasticities between air demand and rail travel time were difficult to estimate.

2.2. Centre-to-centre travel times

As explained by Donners (2016) in their description of the transportation system, airports are usually located a significant distance away from city centres, as opposed to most main railway stations belonging to a city. Additionally, idle time at an airport must be taken into account: this idle time may consist of security checks, check-in, baggage handling and other such activities for the passenger at the airport, as well as taxiing and waiting time for the aircraft between gate departure and take-off and between landing and gate arrival. The total travel time from city to city using air travel is relevant for the estimation of travel demand, as is described above and is the topic of RQ1.

2.2.1. Idle time

Durand and Romijn (2023) and Savelberg and De Lange (2018) estimated idle/wait time at the airport to amount to 2 hours for all 13 destinations from Amsterdam Schiphol Airport considered to have the most potential for air-rail substitution in a competitive environment. This time only accounted for the idle time of the passenger; idle time of the aircraft was considered to be incorporated in the scheduled flight time (as opposed to the physical flight time between take-off and landing).

2.2.2. Airport access and egress

Donners (2016) calculated access and egress time specifically for each airport using great circle distances to the coordinates of the geographical city centre, mode-specific detour factors and speed averages.

In the studies of Durand and Romijn (2023) and Savelberg and De Lange (2018), the sum of access and egress time to and from airports was estimated to be two hours in all 13 cases. However, an access and egress time to and from railway stations of one hour was estimated as well.

Rothfeld et al. (2019) analysed access and egress travel times for 22 European airports using Google Maps (Google, n.d.-a) and found large variance in these travel times. The most significant difference was between transport modes (public versus private), the most extreme example being Madrid airport with travel time averages (weighted by population) of 24 minutes for driving versus 95 for transit. Travel times also varied between different airports, e.g. 55 minutes for transit at Amsterdam airport versus the aforementioned 95 of Madrid. Other significant influencing factors included the time of day (day versus night) and the location of the passenger's origin or destination (urban versus rural).

2.3. Night train attractiveness

This section describes factors that influence passengers' preferences for and attractiveness of long-distance night trains. These factors can be of use to all RQs, in order to confirm that the RQs are relevant and appropriate to address the topic and research gap at hand.

Weisshaar (2024) investigated the influence of various factors on passenger preferences for very-long-distance (1400-1600 km) night trains through a stated preference survey of Dutch travellers. The survey concerned a case study of an Amsterdam to Barcelona trip with a choice between airplane, high speed train and night train. Curtale et al. (2023) researched passenger preferences for long-distance travel by night train based on a stated preference survey of Swedish residents, with a focus on trips for touristic purposes. Heufke Kantelaar (2019) performed a Stated Preference survey on traveller choices between night train, morning plane and evening plane plus hotel for reaching a destination.

2.3.1. Comfort and ticket prices

One major factor determining the attractiveness of the night train was found in all three of these studies to be accommodation. The newly introduced mini-cabin accommodation category was found to be highly attractive (Weisshaar, 2024). This is supported by Heufke Kantelaar (2019) who identified the level of comfort, the type of compartment, and particularly the level of privacy to be important determinants of the attractiveness of the night train in an explicit air-rail substitution context. As mentioned before, a low-comfort night train aimed at substituting low-cost flights would be significantly less attractive and have a 20-25% smaller market share in a competitive environment (Heufke Kantelaar, 2019).

The other major factor was ticket prices, both of flight and night train (Weisshaar, 2024; Curtale et al., 2023; Odendahl, 2020), although price sensitivity is somewhat higher for plane than night train (Heufke Kantelaar, 2019). Policy makers can heavily influence the night train's market share (Curtale et al., 2023): this would increase from 40% to 72% if subsidies were provided for the operation (Weisshaar, 2024). Although such policy would better harness societal benefits of the night train, no conclusion was drawn on whether these benefits are worth the subsidies. It must be noted that air travel itself currently enjoys a wide range of subsidies for a variety of purposes, including the support of (otherwise) unprofitable services (Fichert, 2020).

2.3.2. Role of travel time

Travel time of the night train itself is a more divisive factor. Although 10 hours (Bird et al., 2017) and 13 hours (Weisshaar, 2024) are stated to be optimal night train travel times, longer travel times would be no deal-breaker, and a travel time reduction of 2.5 hours (*ceteris paribus*) would only lead to a 5% increase in market potential (Heufke Kantelaar, 2019). However, infrastructure investment to reduce travel time can serve as a main innovation to attract current plane users to the night train (Curtale et al., 2023). The option of high-speed night trains, following the example of China, is mentioned in multiple studies (Heufke Kantelaar, 2019; Savelberg, 2019), but several engineering and financial barriers exist for this (Savelberg, 2019).

Travellers have a slight preference for a morning arrival time of 10:00 over 8:00, although the 8:00 arrival time does increase utility in some cases, mostly for business-oriented trips (Heufke Kantelaar, 2019). A (low) willingness to pay for for few intermediate stops is found as well, although Heufke Kantelaar (2019) does note that the nature of a Stated Preference survey may cause underestimation of the willingness to pay: are travellers truly aware of the benefits of fewer stops (i.e., reduction of disturbance from other passengers boarding and alighting) if they are not experiencing it themselves?

With access distance not affecting travellers' choices in Weisshaar (2024)'s study, the catchment area of a night train is concluded to be quite large. Punctuality is an equally insignificant factor, implying no need for timetable buffer (Weisshaar, 2024).

Night train travel times in earlier studies were determined by having survey respondents estimate the travel time (Heufke Kantelaar, 2019) or using a generic speed average of 80 km/h (Savelberg, 2019).

2.3.3. Traveller preferences

Four classes of travellers with varying characteristics and preferences were identified by Weisshaar (2024), as summarised in Table 2.2. Trip purpose (leisure or business) was found to not influence the class of a traveller, nor did variables such as experience with train travel and socio-demographic factors (apart from age).

As noted by Weisshaar, their research was limited by a "highly questionable" (*sic*) assumption of a 100€ hotel stay accompanying every flight trip, a bias towards train affinity in the survey panel, and a general difficulty of applying a stated preference survey to estimate market shares. The results were "heavily dependent" on these assumptions and may have inflated the potential market share estimated for the night train (Weisshaar, 2024). Additionally, the author noted that their study can only be generalised to countries with an existing dense high-speed rail network. In regions where this does not apply, the night train's market share is expected to be higher, due to a lack of competition from high-speed rail services (Weisshaar, 2024).

Segment name	Share	Primary decision factor	Secondary decision factor(s)	Remarks
Environmentally conscious comfort lovers	13%	Accommodation	Booking convenience	Choosing environmentally friendly modes even when inconvenient
Experienced night train travellers	29%	Flight cost	Accommodation, night train cost	Small influence of booking convenience
Cost-sensitive travellers	37%	Ticket price	Accommodation	Less environmentally concerned and younger people
Flight lovers	20%	Accommodation	Little intention to use environmental modes	High initial preference for airplane

Table 2.2: Summary of the demand segments for long-distance travel identified by Weisshaar (2024).

2.4. Demand modelling

This section describes literature concerning the estimation of long-distance rail travel demand, relevant to RQ1 and RQ2.

2.4.1. Long-distance demand modelling example

Donners (2016) investigated the potential demand and supply for international passenger rail travel within Europe in a scenario based on cooperation between operators (and other actors) and on the reduction of existing barriers, both for 2015 and for three growth scenarios for 2030. Main barriers include borders of states, languages and the Schengen free trade area.

Donners used a broad approach, as shown in Figure 2.2 as an illustration of existing methodology in long-distance transport modelling. It develops the network through calculations of passenger-trips and seating capacity. These used as inputs for choice modelling: the population, GDP and education level of 125 cities, perceived barriers and distance, and the assumption of travel time sensitivity and resulting minimisation by potential passengers.

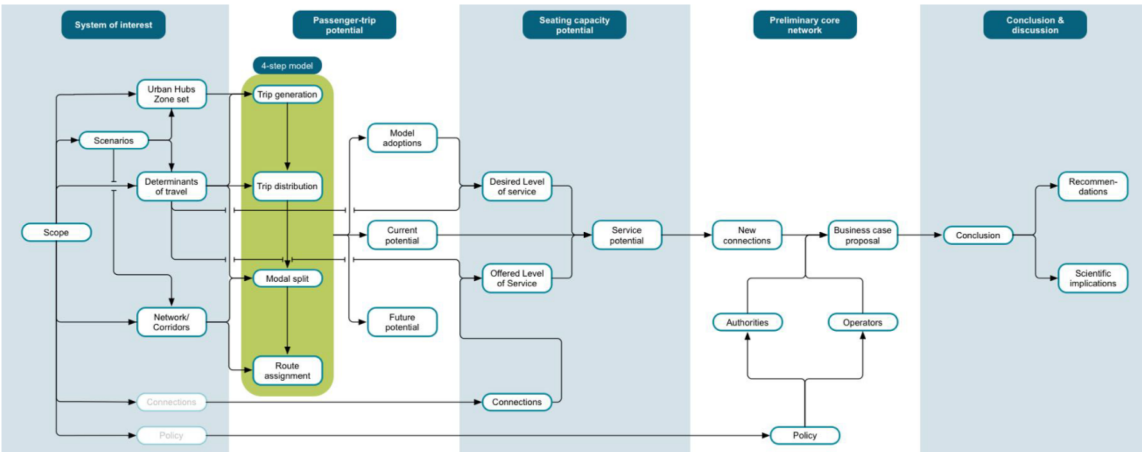


Figure 2.2: The modelling framework used in Donners (2016).

Donners modelled three different networks (road, rail and air) available for use by five modes: car and bus, high-speed and conventional rail, and airplane, respectively. The model used a graph with direct links between several types of hubs: the aforementioned 125 cities and their associated airports (for calculating access/egress times), 50 additional nodes, and maritime links where fixed links are missing. As opposed to using current travel times (Durand and Romijn, 2023; Savelberg and De Lange, 2018), Donners calculated distances and travel times on these links using great circle distances and mode-specific speed averages and detour factors. The core of the network was based on then-current and future air networks and EU TEN-T transport corridors.

For modelling the passenger-trip potential, Dios Ortúzar and Willumsen (2011)'s 4-step transport model was applied as follows:

1. **Trip generation** was performed using the annual average of long-distance tours for Europeans and the GDPs/capita for all cities in the model.
2. **Trip distribution** was performed with a gravity model, which was deemed suitable thanks to a good fit for modelling and its ability to easily account for barrier effects of national, linguistic and trade borders.
3. **Mode choice** was performed with Chorus et al. (2008)'s Random Regret Minimisation, which expands on Random Utility Maximisation by incorporating how the attractiveness of one alternative is affected by the performance of other alternatives. Travel time was found to be the main indicator of mode choice, although additional attributes are preferred to be included in transport modelling.
4. **Route assignment** was performed with Dijkstra's Shortest Path algorithm and all-or-nothing assignment based solely on travel time minimisation.

Existing services were characterised by their seating capacity, frequency, transfer number and quality, train category (based on speed and stopping pattern of three different long-distance daytime train types) and travel time performance with regard to the distance covered. These indicators were used to determine the effective number of seats offered, in order to determine how well capacity serves the demand.

It is important to note that Donners (2016) considered night trains to be suitable for long-distance travel, yet disregarded them in his modelling. Mainly the fact that night trains provide a combination of a sleeping berth and travel made them so unique that they could not be modelled in the same way (with similar assumptions) as the other modes in their research.

Donners (2016) found a 22% increase in total trip potential across all modes, and a five-fold increase in international rail trip potential. Potential rail demand is almost 60% higher than the supply when it comes to international travel. A full implementation could save up to 28 million tons of CO2 emissions in the 2030 maximum growth scenario. The modal split in each scenario is shown in Figure 2.3. The role of bus travel on medium and long distances (over 300 km) is found to be negligible, as is that of the car on long distances (over 600-700 km). The authors stated that routes with fewer than 250,000 annual trips (translating to circa 700 daily trips) in a single direction are insignificant with regard to current economics of railway operators. Additionally, the authors emphasise that rail connections should not only be fast, but also frequent, reliable and easy to find in order to attract passengers. Some key limitations to Donners (2016) include a lack of reliable and consistent available data, the aggregation of metropolitan regions required to model long-distance travel, the blind eye turned to origins and destinations outside the 125 investigated cities, and the use of GDP/capita and willingness to travel for trip generation purposes of which the accuracy was unclear.

2.4.2. Night train demand

Odendahl (2020) focused on air-rail substitution with night trains specifically for touristic trips. Following a hypothesis that tourists would be inclined to choose a different destination for their trip if flights are replaced with (slower) train services, trip distribution was remodelled for a scenario in which flights were less attractive. For this purpose, a gravity model was used (similarly to Donners (2016)) with adaptations to model trip attraction between selected touristic origins and destinations. In the current environment, air travel is significantly more attractive for touristic trips compared to the night train. Reasons for this imbalance range from travel time, ticket prices and capacity offered (Odendahl, 2020), to increased railway infrastructure usage fees, comparatively high operational costs due to the nature of night trains and the lack of a level financial playing field with air travel (Savelberg, 2019). According to Odendahl (2020), the most attractive night train routes for touristic purposes already exist, and following the modelling process, only few potential routes are found to be promising additions. However, these routes as well as existing routes operating sub-optimally are hindered primarily by border and policy barriers. It becomes clear that any significant replacement of flights with touristic purposes will require a structural change in the playing field between air and rail to reduce competition by air travel. Without policy or market changes, the potential routes are not attractive and cost-effective enough for rail

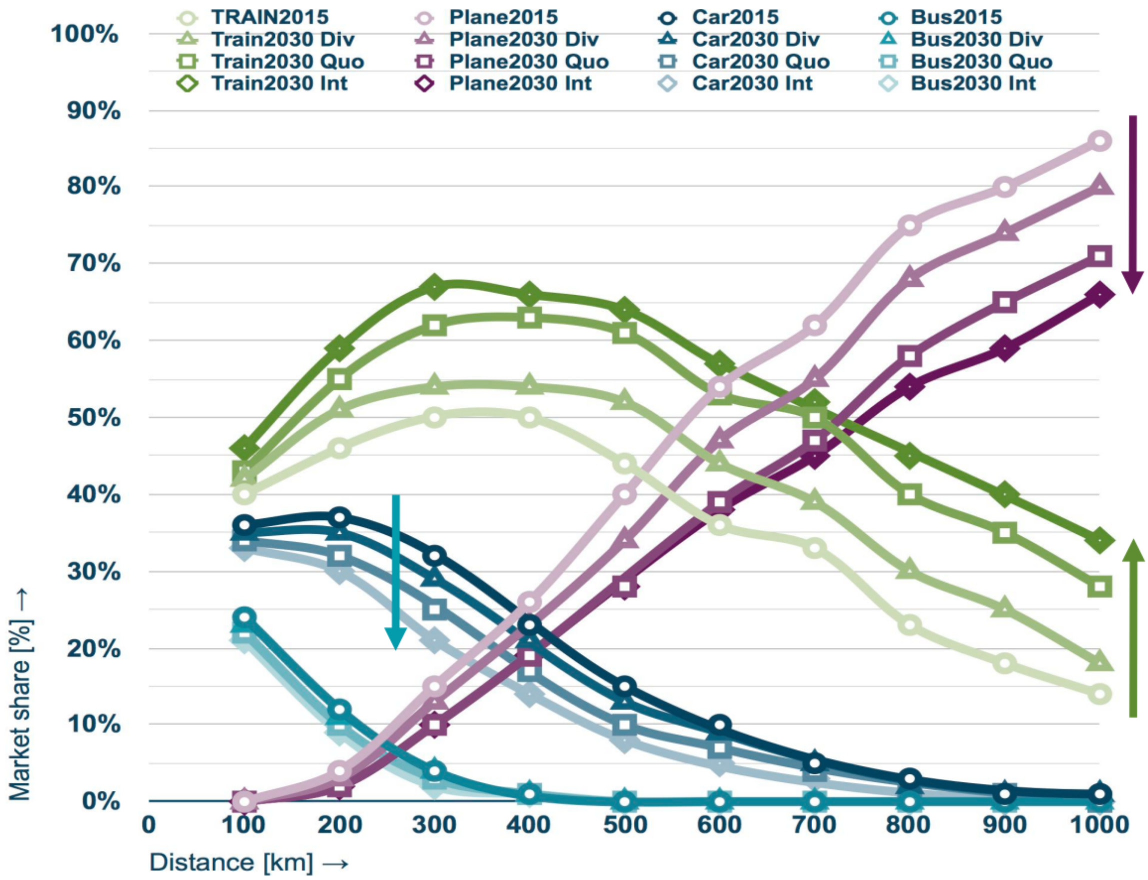


Figure 2.3: The modal split for optimised European passenger rail in 2015 and 2030 (in three growth scenarios) as determined by Donners (2016).

operators to introduce services on (Odendahl, 2020). Odendahl (2020) reflects that although the application of the gravity model provides a good overview of promising routes for night trains to substitute air travel, this merely serves an indicative purpose. More detailed conclusions on the attractiveness of such routes would require specific case studies into each route.

Provided that the comfort level of a night train offer is on par with currently existing services, the market share for the night train (as opposed to evening plane and morning plane) is estimated at around 60% for both business and leisure travel combined (Heufke Kantelaar, 2019). A low-cost, low-comfort night train, as a direct alternative to the similar category of flights, would have a 20-25% smaller market share (Heufke Kantelaar, 2019). Optimisation of the night train's timetable only leads to an increase of this market share by a few percentage points, according to Heufke Kantelaar, corresponding with the earlier finding that the value of time for night trains is relatively low compared to other modes. A more significant improvement in mode share potential is found in the introduction of new rolling stock with a focus on comfort and luxury, raising the potential market share to 67% (Heufke Kantelaar, 2019). Specifically for the travel relations Netherlands-Vienna and Netherlands-Milan, assuming uniform demand across the entire year, Heufke Kantelaar estimates daily one-way demand at 120-140 Dutch passengers; however, this does not include passengers from markets of other countries served by trains on such routes. However, regarding the above findings it must be noted that this study only considered a somewhat specific context scenario: a trip of 12-14 hours for either business or leisure, with 1 or 2 passengers, and with an objective to arrive at the destination in the early morning; trips outside this scope have not been taken into account (Heufke Kantelaar, 2019). Night train demand is mainly expected to come from air travel substitution, and the generation of new demand by the introduction of a new night train service would be very limited (Bird et al., 2017).

Savelberg (2019) investigated the scale night train demand potential on eight routes from the Netherlands to major destination cities (>1 million inhabitants) at a distance between 789 (Copenhagen) and 1,191 (Warsaw) kilometres as the crow flies from Amsterdam, assuming an average speed of 80 km/h and the removal of financial and regulatory barriers and infrastructural capacity constraints. Savelberg (2019) stated that insufficient data was available for quantitative demand estimation, namely the current trip total to/from the destinations, growth predictions and the share of travellers switching to night trains if these become available. A supply-oriented approach, assuming night trains with fixed capacity (250 passengers per connection) and average load factor (50% across the entire year) to be introduced on eight different routes, estimated 720,000 annual passengers, or 12% of then-current flight demand on each of the routes, with a potential increase to 1 million annual passengers if the average load factor could be increased to 70% (Savelberg, 2019).

2.4.3. Split between day and night travel

When it comes to RQ2, after estimating the rail demand resulting from full air-rail substitution, the question is what share of this demand is to be allocated to night train travel, as opposed to daytime trains. (Other modes, such as car, rail and bus, are ignored due to their marginal role in long-distance transport as seen in Figure 2.3.) Unfortunately, no literature was found on mode shares in an exclusive competition between night trains and day trains. Mode shares for night and day train that were found in literature included air travel as a competing mode; no clear evidence was found on whether those air passengers would distribute themselves across night and day trains in the same ratio if air travel were removed as an option. Heufke Kantelaar (2019) did observe a correlation in preferences for travel by morning plane and night train, as opposed to evening plane (plus hotel).

Time-of-day choice modelling for long-distance trips could provide insight in distributions between night and day travellers. However, this topic has received very little attention in scientific literature as of 2024. Jin and Horowitz (2008) conducted a survey to develop a multinominal logit model estimating time-of-day choice for long-distance trips. They identified differences and similarities between local (urban) and long-distance trips.

A range of relevant factors in time-of-day choice modelling are not present in urban trips but only in long-distance trips: e.g., overnight stays, availability of public transport, or presence of children. These differences are significant enough that long-distance time-of-day modelling requires its own approach and can only at best draw some inspiration from modelling at the urban level.

Jin and Horowitz (2008)'s survey showed a strong influence of travel time and length of stay at the destination, weekday/weekend distinction and travel group composition. Long-distance trips are more occasional than urban trips and have strongly varied characteristics, from rigidly planned ahead to flexible and random. Trip purpose and weekday/weekend distinction were identified as the best indicators to "partly capture" time-of-day decision-making "[i]n an effort to predict the unpredictable", thus implying the weakness of these predictors.

2.5. Summary of literature review

This chapter reviewed various literature regarding long-distance travel and night trains, to support the RQs of this study. Most of this literature regarded various steps of the demand modelling process in RQ1 and RQ2, whereas some provided a broader insight into the context, scope and setup of this study.

Travel time was found or stated to be the most significant determinant of passenger choices in long-distance air and rail travel. However, the value of time for long-distance travellers was found to vary greatly. Different values for demand elasticity of travel time were found in both a general meta-study and a more specific case study of air-rail substitution upon introduction of high-speed rail.

Travel times for long-distance travel were either retrieved from current schedules or calculated using great circle distances and mode-specific speed averages. Airport access and egress times have seen varying approaches, from detailed case studies per airport and the use of distances and speed averages to generic values which also apply to idle times.

Regarding the attractiveness of night trains, both comfort and ticket prices were identified as major factors, with an important role for policies in influencing the latter. The effect of travel time and speed is smaller but noticeable, and preferences for night train travel times were identified. Access distance of night trains is no significant limiting factor to their potential, implying a large catchment area.

For modelling demand, multiple sources all found a gravity model to be a good fit in applications for long-distance travel modelling, including destination changes for touristic trips. Existing studies on air-rail substitution using night trains were found to serve only as an initial indication for promising routes, and demand-based estimations struggled from a lack of data, resulting in supply-oriented estimations; more detailed case studies would be required to determine the exact potential of routes. Borders and policies were identified as key barriers to increases in supply for making night trains more competitive with air travel.

These findings provide an overview of previously applied methods in long-distance travel demand estimation and accurate travel time calculation. The next chapter will outline which of the methods reviewed above will be applied in the research plan of this thesis, for what reason and in what way.

3 Methodology

This chapter describes the datasets used in this research, explains the methodology to answer the research questions, elaborates on the methods used for this purpose, and describes the case study the methodology will be applied on.

3.1. Data requirements and sources

This research makes use of various data sources for various purposes, of which the most important ones are described in this section.

3.1.1. Air travel demand

For data on existing passenger air travel routes and their demand, Eurostat databases by the name of "Detailed air passenger transport routes by country" (Eurostat, 2024c) are used.

For 36 European countries, data is recorded from airports reporting their passenger numbers on each of their routes per month, quarter or year. The database is being updated regularly: at the time of writing in June 2024, the most recent monthly data dates from February 2024. Monthly and quarterly data has been kept since 2000, with annual data going as far back as 1993 (sampled for Germany's and the Netherlands's datasets).

The level of detail of the data varies by country in several ways. First of all, most countries - such as Germany, Austria and the Netherlands - report each destination airport abroad as a separate route: i.e., from reporting airport (e.g., Berlin-Brandenburg) to destination airport (e.g., Stuttgart). However, Czechia aggregates these routes by destination country: i.e., from reporting airport (e.g., Brno-Turany) to destination country (e.g., Germany).

The databases contain routes to destinations all across the world, but can be filtered to only show a custom selection of these. This customization screen is illustrated in Figure 3.1. Either the full database or a customized selection can be downloaded in several formats, including CSV. The metrics measured include:

- passengers on board ("All passengers on board of the aircraft upon landing at the reporting airport or at taking off from the reporting airport. All revenue and non revenue passengers on board an aircraft during a flight stage. Includes direct transit passengers (counted at arrivals and departures)."(Eurostat, 2024b));
- passengers carried ("All passengers on a particular flight (with one flight number) counted once only and not repeatedly on each individual stage of that flight. All revenue and non-revenue passengers whose journey begins or terminates at the reporting airport and transfer passengers joining or leaving the flight at the reporting airport. Excludes direct transit passengers. (Eurostat, 2024b));
- passenger seats available;
- commercial passenger air flights;

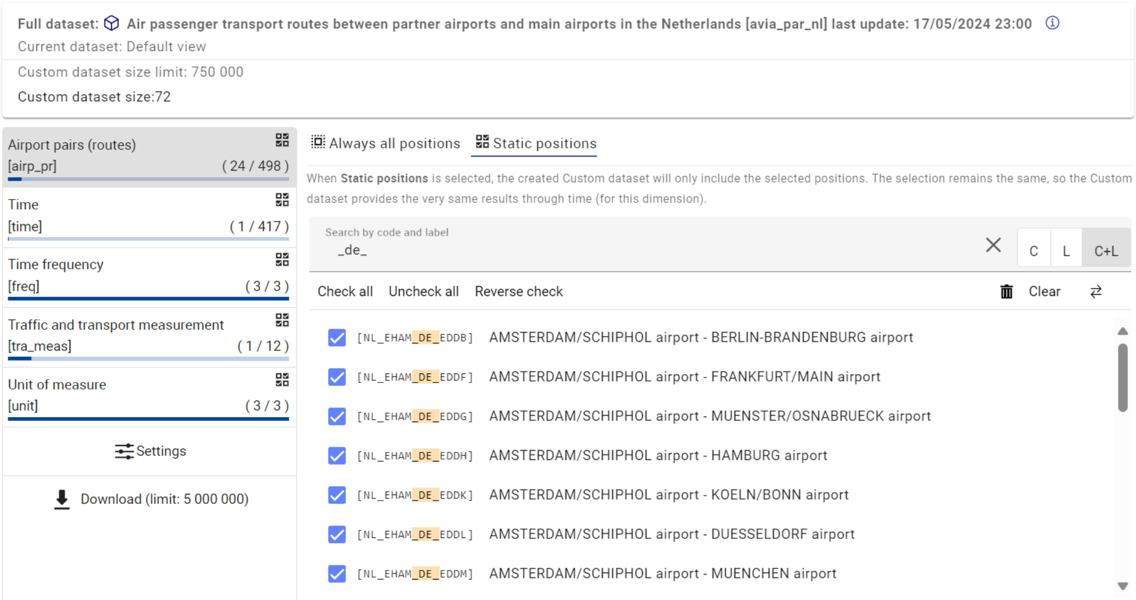


Figure 3.1: Screenshot of the customization screen for the Eurostat database of Dutch air passenger data, showing the option to filter on destination airports in a specific country (here: Germany) using a country code (here: DE).

and each of the above allowing a distinction between arrivals, departures and totals. A full detailed description of these databases is provided at Eurostat (2024b).

This study uses the default 'passengers on board' metric because this gives a higher completeness of the total number of passengers travelling on a flight. As for the temporal dimension, the passenger numbers of 2023 will be used, being the most recent annual data available. Annual data are considered to be preferable in order to avoid seasonality effects of monthly or quarterly data.

3.1.2. Theoretical rail travel times

Rail travel times are retrieved via the Railway Routing tool (Railway Routing, n.d.) which outputs theoretical rail travel times between two (or more) locations on the worldwide railway network. An example of this tool is shown in Figure 3.2. The times calculated by this algorithm are solely based on local line speeds gathered from open source data (OpenStreetMap contributions) and do not take into account differences in acceleration between train types, station stops, and buffer times.

The shortest travel time in either direction is selected. This is particularly relevant for Railway Routing, since it occasionally presumes a specific piece of track can only be used (at its normal speed) in one direction, and not (or at a very limited speed) in the other.[1]

3.1.3. Current rail timetable

An overview of direct train connections in the current timetable is found in Direkt Bahn Guru (Direkt Bahn Guru, n.d.). This online tool shows, for a selected station, an overview of all destinations that can be reached directly (i.e., without transfers), including the shortest timetabled time. An example of this tool is shown in Figure 3.3.

3.1.4. Flight times

Flight times are retrieved via FlightsFrom.com (n.d.). This is a website showing scheduled flights and routes from airports worldwide, including timetables. A snippet of this website is shown in Figure 3.4. In accordance with the strategy for Railway Routing, the shortest flight time of both directions is selected in case of a difference.

This source was preferred over Google (n.d.-a) due to a higher degree of completeness. For instance, Google Maps was unable to find flight times between Frankfurt and Dusseldorf in either direc-

[1] For instance, the fastest route from Vilnius to Riga is 4 hours and 9 minutes via Šiauliai. In the opposite direction, Riga to Vilnius, the result is a route of 5 hours and 20 minutes on a detour via Daugavpils. Forcing the tool to go via Šiauliai in this direction as well yields a travel time of 6 hours and 42 minutes.

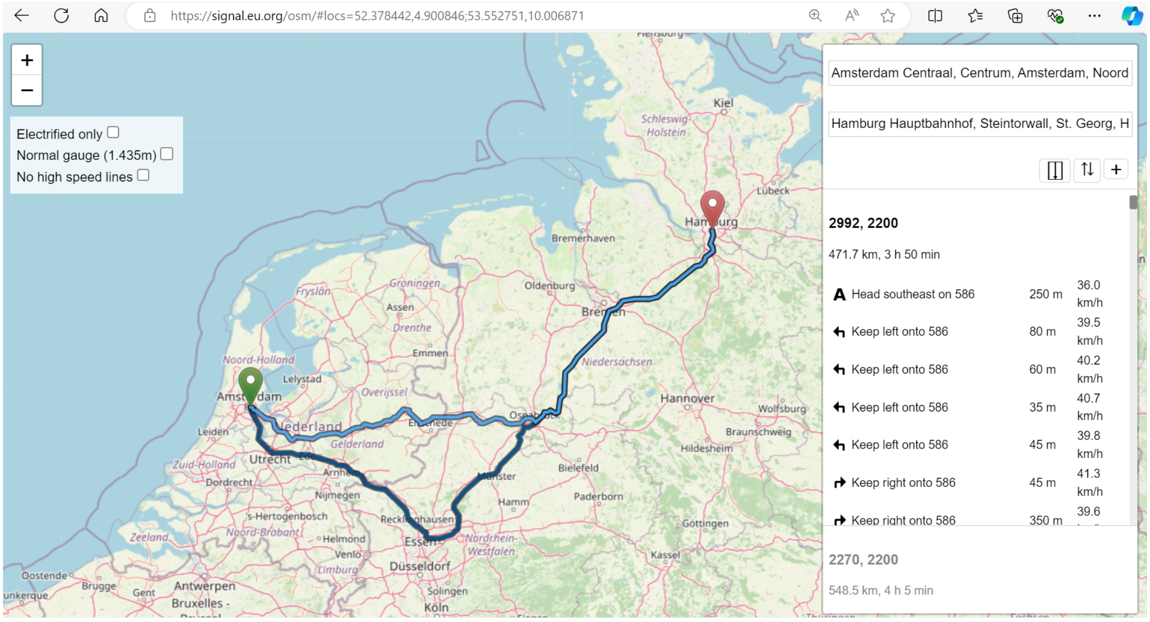


Figure 3.2: An example inquiry of Railway Routing for a route from Amsterdam Centraal to Hamburg Hauptbahnhof, showing two possible routes with duration and length, and the customization tickboxes on the left.

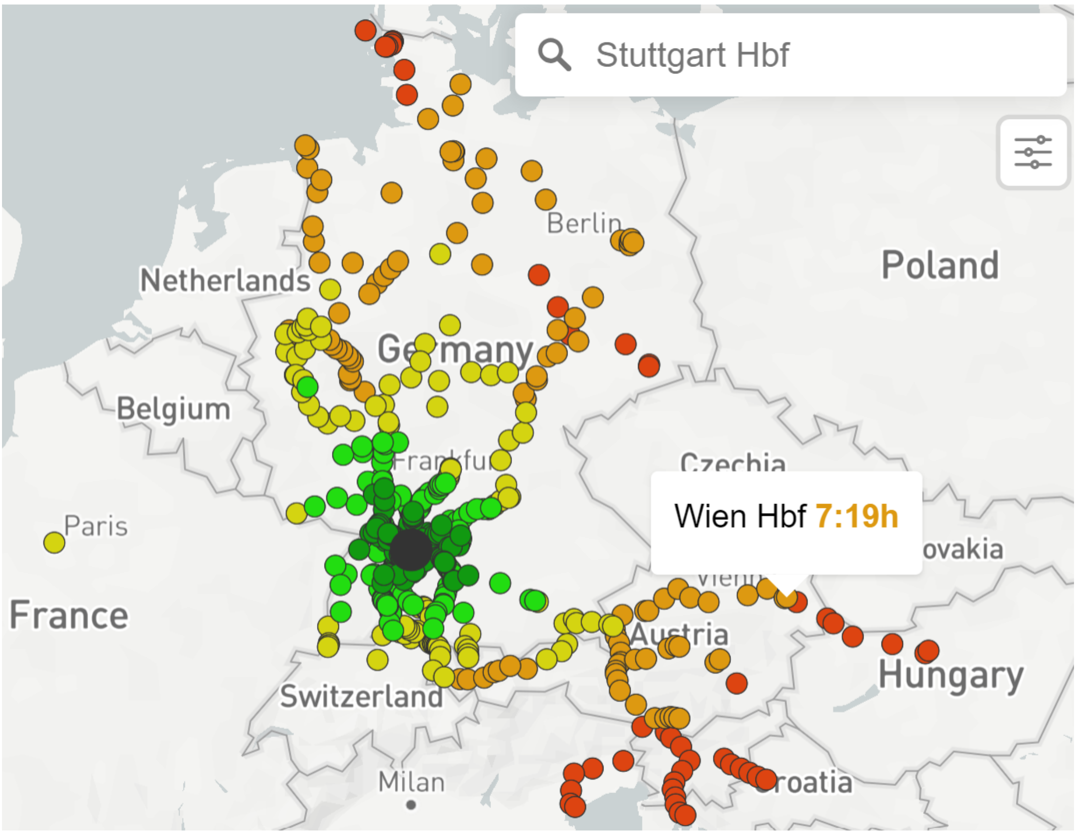
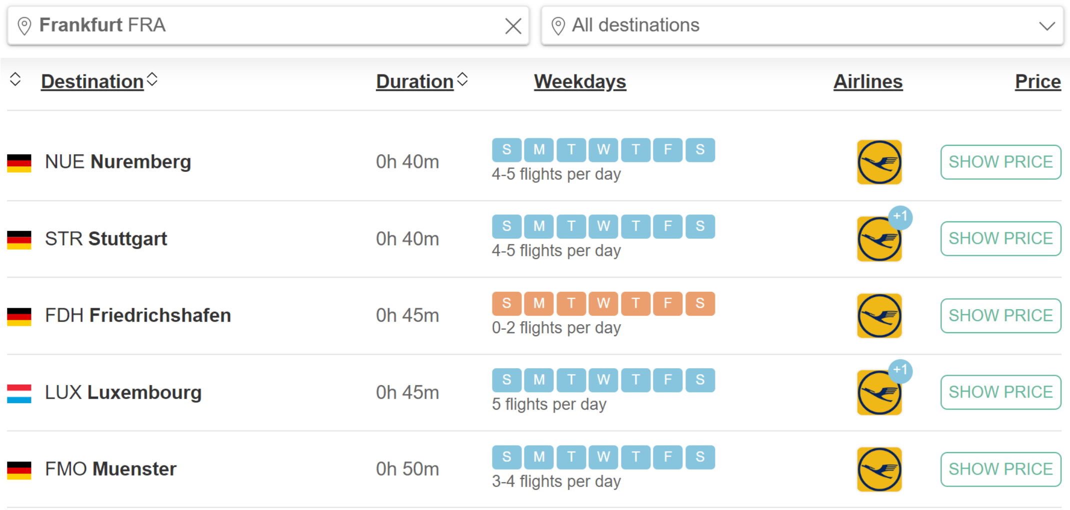


Figure 3.3: An example inquiry of Direkt Bahn Guru for all direct rail connections from Stuttgart's main station. The colors of stations are dependent on the fastest rail travel time from Stuttgart to that station, ranging from dark green (<30 minutes) to red (>8 hours). The connection to Vienna is highlighted.

tion, while this was no issue for FlightsFrom.com. Additionally, FlightsFrom.com retains flight times from direct flight connections which (recently) ceased to exist, such as between Frankfurt and Linz.



Frankfurt FRA | All destinations

Destination	Duration	Weekdays	Airlines	Price
NUE Nuremberg	0h 40m	S M T W T F S 4-5 flights per day		SHOW PRICE
STR Stuttgart	0h 40m	S M T W T F S 4-5 flights per day	+1	SHOW PRICE
FDH Friedrichshafen	0h 45m	S M T W T F S 0-2 flights per day		SHOW PRICE
LUX Luxembourg	0h 45m	S M T W T F S 5 flights per day	+1	SHOW PRICE
FMO Muenster	0h 50m	S M T W T F S 3-4 flights per day		SHOW PRICE

Figure 3.4: Snippet of FlightsFrom.com website inquiry of flights from Frankfurt airport.

3.1.5. Airports and stations

Airport codes and names, their associated city/cities and their coordinates are retrieved using the dataset of Rafiee (2024). This is a table with data on circa 10,000 airports, train stations and ferry terminals worldwide, collected from a variety of sources. It contains, among other variables, the transport terminal's name, the city it belongs to and country of location, its IATA and ICAO codes, and its coordinates. This study uses this dataset to link airports to their associated cities.

For each city in the air passenger dataset, one main railway station is to be selected to serve as the 'central point' from/to which access/egress times to/from the associated airport(s) and rail travel times to/from other cities are calculated. Preferably, this station is both centrally located (to serve as a proxy for the city centre) and well-connected to the surrounding railway network, although this is not always possible. This dataset is to be kept manually, containing for each city the associated station name and the precise coordinates of a well-connected track in that station (in order to allow automation of Railway Routing inquiries). This table of stations is provided in Appendix A.1.

3.2. Travel time calibration

This section describes the methods used to calculate the rail travel time between any two cities, which is to be used for estimating demand later.

3.2.1. Rail travel times

For the scenario at hand in which flights within the scope area are mostly or entirely removed, a reorganisation of railway timetable planning with priority for (international) long-distance services will be likely and/or necessary in order to increase capacity sufficiently (Wesdorp and Moerman, 2021, Donners, 2016) for absorbing additional passengers substituting air with rail. Directly using rail travel times from the current timetable in this research is not preferable, since current rail services may be more focused on local and regional transport than they would be if air travel is no longer possible for long-distance travel, and travel times may thus be sub-optimal for the scenario at hand. This requires a recalculation of rail travel times. As described in Section 3.1, the Railway Routing tool (Railway Routing, n.d.) calculates theoretical rail travel times based on line speeds, but these travel times cannot be used directly since they incorporate no time for stops or buffer. Donners (2016)'s method of using great circle distances and mode-specific speed averages to calculate travel times has been considered, but ultimately discarded because this method does not take into account local and regional differences in rail network coverage and line speeds.[2] For a more specialised study focused on rail such as this, rather than a broader study of more modes such as Donners (2016)'s, a more specific method is preferred.

In order to scale Railway Routing's theoretical times to realistic approximations of optimised travel times, the choice is made to determine a 'calibration factor' for the theoretical times through a compar-

[2] Donners (2016) does correct some travel times based on geographical features, but not based on specific railway infrastructure.

ison with timetabled times for a selection of connections that are already 'optimised' for long-distance travel. A connection will be considered maximally 'optimised' if the following requirements apply:

- The train has relatively few or no stops in cities without airports (as appearing on FlightsFrom.com (n.d.)). This requirement exists to ensure that the connection mainly or only serves major cities that would be most relevant for air-rail substitution.
- The train does not have any stops lasting more than 10 minutes. This requirement exists to ensure, as much as possible, that the travel time of the connection is not extended excessively by long wait times at stations.
- The train is not a tilting train. This requirement exists to ensure that the travel time of the connection can be achieved by regular night trains; no tilting night trains exist in Europe at the time of writing.
- Each country in the spatial scope has at least one calibration route starting, ending, or passing through there. This is to account for possible differences in regulations and timetable approaches between countries. In order to abide by this criterion, the above criteria may be violated if no route can be used for a country, but this violation should be minimal: i.e., having the lowest possible percentage of non-airport cities served, and exceeding the maximal stop duration by the smallest possible amount.

For this master thesis project, it is considered infeasible to generate a fully exhaustive selection of connections that adhere to these standards, due to the large time investment required in either manually researching such connections or automating such a process. It must also be noted that connections may see temporary increases in travel time due to e.g. track works depending on the date for which the timetable is inquired. Therefore, it is recommended to select these connections by hand, while making use of local knowledge on the state of railway services (including service patterns) and infrastructure. Railway operators and infrastructure managers may be a good source for such local knowledge, e.g. by consulting overviews of major track works (DB Fernverkehr AG, n.d.-b) or maps of rail services (DB Fernverkehr AG, n.d.-a).

For the selection of 'optimised' connections as described above, their timetabled times are to be compared with their theoretical travel times according to Railway Routing. Train timetables can be retrieved via, e.g., HAFAS (HaCon, 2024a), with its database accessible via HaCon (2024b).

In order to obtain the desired 'calibration factor', a linear regression model is to be fitted to the data of timetabled and theoretical travel times. The resulting linear function is to be applied to theoretical rail travel times in the remainder of this research in order to estimate its optimised rail travel time.

Finally, in accordance with Durand and Romijn (2023) and Savelberg and De Lange (2018), a fixed time supplement of one hour for access and egress to and from the station will be added to the rail travel time calculated above. This is done in order to maintain consistency with the method of determining airport access and egress times, as explained below.

3.2.2. Air travel times

As per Donners (2016), air travel time from city to city consists of the following components:

- flight time;
- idle/wait time at the airport;
- access and egress time to/from the airport.

Flight times are retrieved via FlightsFrom.com (n.d.); since these are scheduled flight times, they encompass all scheduled time between departure from the gate and arrival to the gate, including taxiing and idle aircraft times.

For **waiting time**, a fixed time supplement of two hours will be added to the scheduled flight time in accordance with Savelberg and De Lange (2018).

For **access and egress time**, a choice must be made between a specific (Donners, 2016, Rothfeld et al., 2019) and a generic supplement. The choice is made to apply a generic time supplement of two hours as per Savelberg and De Lange (2018) for the following reasons:

- Donners (2016)'s method does not take into account differences in local access and egress conditions and only considers distances and public transport speed averages.
- Calculating specific time supplements for each airport would require either large amounts of additional data or a large number of assumptions about flight departure and arrival times, common origin and destination points of travellers, public transport travel times and frequencies etc.
- Such an approach would additionally cause a significant increase in time investment and model complexity compared to Savelberg and De Lange (2018)'s approach.
- Savelberg and De Lange (2018) also take into account access and egress time to and from railway stations, which allows for a more fair comparison between air and rail; ignoring this station access and egress time would lead to an unfair modelling advantage for rail compared to air.
- Savelberg and De Lange (2018)'s methods are already being applied for airport waiting times and railway station access/egress times. Applying their methods in more parts of this research increases consistency and allows for easier assessment and comparison of results, as opposed to 'cherry-picking' many different methods from many different studies unrelated to each other, which could lead to confounding in calculations.

3.3. Demand estimation

This section describes the process and calculations used to obtain estimations of full rail demand (for RQ1) and night train demand (for RQ2) for the scenario at hand of maximum air-rail substitution.

3.3.1. Gravity model

The essence of a gravity model in transport modelling is the assumption of a linear inverted relation between travel distance or time and travel demand. For the exact magnitude of this linear relation, the travel time elasticity of demand can be a good indicator. However, as discussed in Section 2.1.2, estimations of this elasticity vary greatly, and reliable values specifically targeting air-rail substitution could not be found, let alone such values for 'enforced' air-rail substitution as is the case in this research.

It is decided to opt for the travel time elasticity value of -1.0 as found in Börjesson (2014). The reasoning behind this is that this value comes from a study specifically targeting cross-effects between air and rail, which is considered to be the closest approximation to the maximum air-rail substitution scenario used in this study.

However, it must be noted that travel time elasticity values as originally intended are not directly applicable to a hypothetical research such as this, which features considerable travel time increases on many journeys. For an elasticity of -1.0, this would mean that a 100% increase (or doubling) in travel time reduces estimated demand by 100%, in other words, to zero. A direct application of a -1.0 elasticity would thus mean that travel demand on relations such as Madrid-Rome and Barcelona-Rome (having 4,800 and 4,100 daily air passengers each way and being the 10th and 11th most popular air routes in the scope area, respectively) would cease entirely, which the author does not consider realistic. In order to avoid this problem, it is opted instead to apply the elasticity value as a multiplication factor within the gravity model. This means that, with a -1.0 elasticity value, a 100% increase or doubling of travel time (multiplication by 2) causes a 50% decrease or halving of estimated demand (division by 2).

The gravity model will estimate additional rail demand for a city pair in a maximum air-rail substitution scenario through the following **simple demand mutation formula**:

$$D_{rail} = D_{air} * (1 - e_{tt} * \frac{TotalTime_{air}}{TotalTime_{rail}} - 1)$$

in which D represents the demand, $TotalTime$ represents the total travel time of a mode (i.e., including idle and access/egress time) and e_{tt} the travel time elasticity of demand. As an example, with the selected elasticity value of -1.0: if the total rail travel time on a connection is four times that of air, it is assumed that 25% of recorded air passengers will proceed to travel by train. The remaining 75% are assumed to choose to either not travel at all or travel to a different destination.

When specifying the components of total travel time, this leads to the following **specific demand mutation formula**:

$$D_{rail} = D_{air} * (1 - e_{tt} * \frac{tt_{air} + ae_{air} + idle_{air}}{Calib(tt_{rail}) + ae_{rail}} - 1)$$

in which tt represents the current duration of the flight or train ride, $Calib()$ represents the calibration function applied to rail travel times, ae represents the access/egress time of a mode to and from the airport/station, and $idle$ represents the idle time of a mode at the airport/station. The idle time for rail is considered to be zero and thus omitted from the formula.

When this demand mutation formula is applied to daily one-way passenger numbers on city pairs, it is referred to as the **full Estimated Daily One-way Demand (full ED1D)**.

3.3.2. Day/night demand share

After estimating the rail demand resulting from full air-rail substitution using the gravity model above, the question is what share of this demand is to be allocated to night train travel, as opposed to daytime trains. Unfortunately, no literature was found on mode shares in an exclusive competition between night trains and day trains. Mode shares for night and day train that were found in literature included air travel as a competing mode; no evidence was found on whether those air passengers would distribute themselves across night and day trains in the same ratio if air travel were removed as an option.

For this reason, a new method must be devised to determine this modal split between night and day trains. It is proposed to estimate the modal share of night trains in this case according to the following **simple night share formula**:

$$share_{night} = min(\frac{max(TotalTime_{rail} - MinNightTravelTime), 0)}{MaxDayTravelTime - MinNightTravelTime}, 1)$$

in which:

- $share_{night}$ represents the share of night train demand as part of the entire rail demand substituted from air travel on a city pair;
- $TotalTime_{rail}$ (in minutes) represents the total travel time of rail (including access and egress time) on that city pair;
- $MinNightTravelTime$ (in minutes) represents the minimum total travel time (including access and egress time) required for night train demand to exist on a city pair, i.e., below this threshold the demand share of night train is 0%;
- $MaxDayTravelTime$ (in minutes) represents the maximum total travel time (including access and egress time) for which day train demand exists, i.e., above this threshold the demand share of night train is 100%.

This estimation method is based on the assumption that travellers' ideal departure or arrival times (i.e., when not constrained by schedules of transport modes) are distributed uniformly across the active hours of the day (i.e., the time of day during which they are willing to travel). When a journey is short enough that it cannot bridge the inactive hours of the day (in other words, the night), travellers are unwilling to take the night train; when a journey is long enough that its travel time does not fit within the active hours of one day, travellers insist on taking the night train.

With no literature found regarding willingness to travel at different hours of the day or a potential limit to daytime travel duration, an assumption is made that people spend roughly one-third of their day (or 8 hours) sleeping or performing sleep-related activities, and two-thirds of their day (or 16 hours) being active. In line with what was described above, and given the access/egress time of rail being 1 hour as per Durand and Romijn (2023), this implies that journeys with a rail travel time (excluding access/egress) under 7 hours ($8 - 1 = 7$) are too short for overnight travel demand to exist, and journeys with a rail travel time (excluding access/egress) over 15 hours ($16 - 1 = 15$) are too long for comfort for daytime travel. Note that day train demand share does not exclusively imply that a traveller completes their journey within one day: they may also stay overnight in an intermediate stop during their journey. However, the share of travellers making journeys of more than 15 hours during daytime with such overnight stays is considered negligible for this research.

The resulting night train demand share depending on travel time is shown in Figure 3.5. This demand share function is also denoted as Demand Share Function (DSF) 7-15, since night travel demand starts at 7 hours of rail travel time and daytime travel demand ends at 15 hours. As an illustration, a route with a calibrated rail travel time of 11 hours would have a 50/50 split between day and night train travel demand.

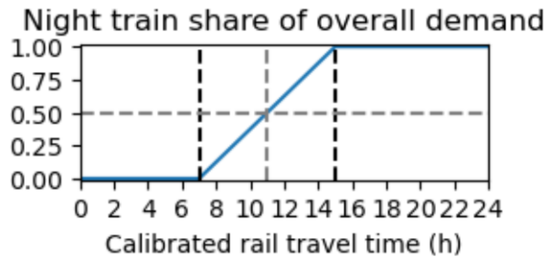


Figure 3.5: Demand Share Function (DSF) 7-15: the demand share of the night train (vs. day train) with 16 active hours per day, showing calibrated rail travel time excluding total access and egress time of 1 hour.

The total night train demand on a city pair is calculated by multiplying the demand mutation formula and the night share formula, together forming the **simple night train demand formula** as follows:

$$D_{NT} = DemandMutation * NightShare$$

$$= D_{air} * (1 - e_{tt} * (\frac{TotalTime_{air}}{TotalTime_{rail}} - 1)) * min(\frac{max(TotalTime_{rail} - MinNightTravelTime), 0)}{MaxDayTravelTime - MinNightTravelTime}, 1)$$

When specifying the components of total travel time and inputting the parameter values of travel time elasticity, access/egress and idle times, minimum night travel time and maximum day travel time, this yields the following **applied night train demand formula**:

$$D_{NT} = D_{air} * (1 + 1.0 * (\frac{tt_{air}/60 + 4}{Calib(tt_{rail})/60 + 1} - 1)) * min(\frac{max(Calib(tt_{rail})/60 - 7), 0)}{8}, 1)$$

Note that the division of travel times (measured in minutes) by 60 implies a conversion to hours, in line with the parameter values.

The remainder of this thesis will frequently use a demand metric called the **night train Estimated Daily One-way Demand (night train ED1D)**. This stands for the applied night train demand formula with daily passenger numbers in each direction used as input and output.

3.4. Operational and performance indicators

This section describes the various operational performance indicators used to assess the results of RQ1 and RQ2 and the methods used to obtain these indicators, thereby answering RQ3.

3.4.1. Night train rolling stock baseline

To obtain a value for a standard capacity of a night train as a means of placing demand estimation values into context and interpreting them, the 'new generation Nightjet' as introduced by Austrian railway operator ÖBB (ÖBB, 2023) is used. The first train of this type was introduced into commercial service in 2023, as part of a total order of 33 trainsets. To the best knowledge of the author, this new Nightjet is as of 2024 the only night train rolling stock in continental Europe functioning as a fixed formation (as opposed to a combination of individual carriages), as well as the night train with the highest maximum operational speed (230 km/h). Furthermore, it is the first and (so far) only night train in Europe to feature the so-called 'mini-cabins', an accommodation type providing single sleeping berths with full privacy (as opposed to larger compartments with multiple beds). These mini-cabins are an example of accommodation innovations that have a significant positive impact on the attractiveness of night trains (Weisshaar, 2024, Curtale et al., 2023, Heufke Kantelaar, 2019). The new generation Nightjet has a total capacity of 320 passengers across various different accommodation comfort categories: sleeper, mini-cabin, couchette and seat (ÖBB, 2023).

3.4.2. Rolling stock indicators

Several metrics will be used to either (or both) assess the quality of the solutions generated in RQ1 and RQ2, provide a more intuitive and accessible impression of the results and their implications, and/or assist in formulating policy recommendations.

The demand estimations per city pair for both full (RQ1) and night train (RQ2) demand are to be assessed by measuring the total resulting demand over all city pairs. Next, to give an idea of the scale at which (additional) rolling stock would need to be purchased or deployed, the total amount of required rolling stock (without distinction between daytime and night travel) can be calculated as follows:

$$RollingStockNeeded_{type} = \frac{2 * \sum_p D_p * Calib(tt_{rail,p})}{c_{type} * t_{operational}}$$

in which:

- $RollingStockNeeded_{type}$ represents an estimation of the amount of rolling stock of a specific type needed to satisfy the entire estimated demand in the scope area, assuming for convenience that this demand were distributed such that it could be served by this rolling stock perfectly efficiently (i.e., without empty seats or demand spillage);
- the multiplication factor of 2 represents the fact that rolling stock is required to run services in both directions (whereas the estimated demand is one-way);
- $\sum_p$ represents the sum over all city pairs;
- D_p represents the estimated demand of a city pair;
- $Calib(tt_{rail,p})$ represents the calibrated rail travel time of a city pair;
- c_{type} represents the seat capacity of a rolling stock type;
- $t_{operational}$ represents the time within a day during which a trainset is assumed to be in commercial service.

$\sum_p D_p * Calib(tt_{rail,p})$ can also be designated as the sum of **passenger hours**, the total number of hours spent travelling by all passengers each way within the time span the demand is expressed in. For consistency with the number of active hours in a day as discussed earlier, $t_{operational}$ is set to 16 hours. This does not imply that passengers can only travel up to 16 hours; they may travel overnight and/or split up their journey across multiple days.

Similarly, for assessing the results of RQ2, the amount of required rolling stock can be obtained, albeit now in a more simple way. After all, whereas a daytime trainset may do multiple runs in a day depending on travel time, night train rolling stock only operates once per night regardless of the route duration. The required rolling stock can thus be obtained as follows:

$$NighttimeRollingStockNeeded_{type} = \frac{2 * \sum_p D_p}{c_{type}}$$

with the multiplication factor of 2 representing the fact that two trainsets are required to run a route every night in both directions. It is assumed for convenience that each night train route can be covered in 24 hours from origin to destination station, including turn-around times, allowing a trainset to return to its origin after two nights and thus requiring 2 trainsets for a nightly service. Issues with potential long-distance routes that take a longer operational time than 24 hours (and would thus technically require additional trainsets to operate a nightly service) are assumed to be resolved. One method to resolve such an issue is to combine the rolling stock circulation of such a long route with a route significantly shorter than 24 hours in order to still require an average 2 trainsets per route. For instance, one might combine the rolling stock circulation of a long Alicante-Oslo route with a short Oslo-Paris route, such that a trainset starting in Alicante would operate Alicante-Oslo-Paris-Oslo-Alicante and return to Alicante after four nights, thus requiring 4 trainsets to operate 2 nightly routes. Another method is to shorten the route of the night train itself and have passengers who intended to travel the full length transfer onto a day train. For instance, Alicante-Oslo passengers may be served by a Barcelona-Copenhagen night train (which is assumed for this example to satisfy the maximum operational time of 24 hours), requiring the use of a feeder day train from Alicante to Barcelona and another from Copenhagen to Oslo for the first and last stretch of their journey.

Note that the rolling stock requirements only result from the demand estimations and do not influence these estimations. The process from demand estimations to rolling stock requirements is linear and does not contain a feedback loop.

3.4.3. Other demand indicators

Aside from the rolling stock-related indicators, the city pair demand estimations are to be aggregated to **city-level aggregated demand**. This demand indicator is the sum of the demand estimations for all city pairs to or from a specific city (e.g., Paris). Similarly, the **country pair-level aggregated demand** is the sum of demand estimations for all city pairs between cities in specified country A (e.g., Netherlands) and cities in specified country B (e.g., Italy). These indicators allow to conveniently explore which cities and countries have the strongest potential demand for daytime or night trains, and between (or within) which countries the largest demand potential exists.

Finally, the country-level aggregated demand can be used in a **comparison with existing night train routes**, the latter being retrieved from a map of night train services such as Maier (n.d.). This comparison is meant to provide a rough idea of where demand is currently being met, and give pointers to currently existing barriers for night train transport. For instance, if relatively many domestic services but few international services from the resulting network are currently already operational, this could indicate country borders as an important barrier.

3.5. Case description

This section provides key statistics about the scope area, the main Eurostat dataset and rail travel times between the cities in the scope area used for the case study of this thesis.

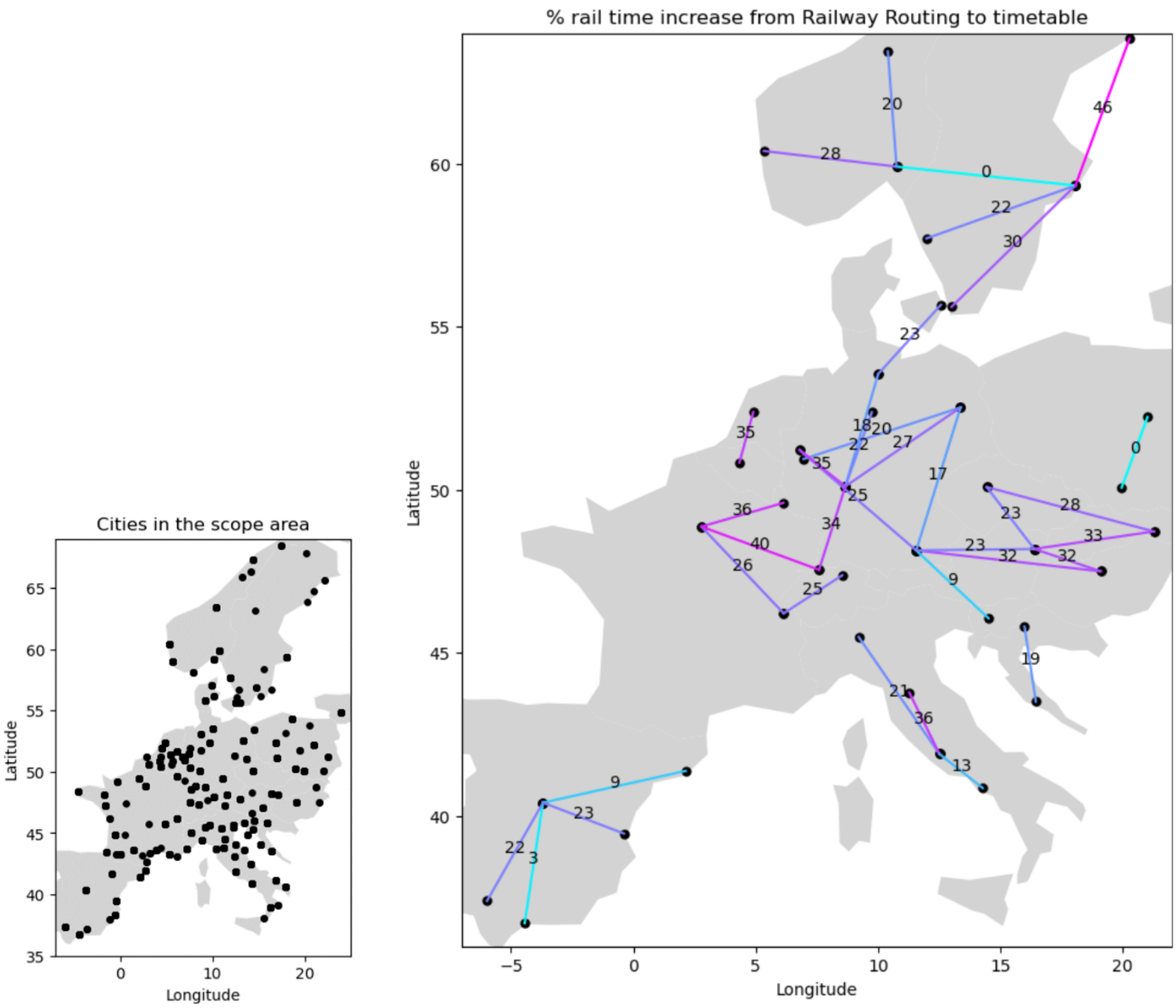
The scope area consists of 157 airports in 150 cities in 19 countries; these cities are shown in Figure 3.6a. In Lithuania, only Kaunas was included since this is currently the only city accessible by normal-gauge railway. In Spain, only cities accessible by normal-gauge railway directly from France are included; although several cities in the northwest of the country have normal-gauge railway access, the track layout in the Madrid area does not allow a normal-gauge train to run from Barcelona (and France) to those cities without reversing multiple times on the high-speed line (Railway Routing, n.d.). Across several countries, a total of 74 cities that are not physically connected to the European mainland (including overseas territories), do not have any railway access or only have broad-gauge railway access have been excluded.

The Eurostat database (Eurostat, 2024c) has recorded flights between 1,323 unique city pairs in the scope area in the year 2023. In total, these city pairs have seen 126 million flight passengers each way across the entire year, or an average of 345,000 daily passengers each way. Average daily flight passenger numbers for individual city pairs range from 4 for Lublin-Gdansk (1,597 annually) to 3,887 for Nice-Paris (1,419,000 annually) each way. The 6 city pairs with the most flight passengers all concern journeys to/from Paris.

3.5.1. Rail travel time calibration

Figure 3.6b shows the 36 city pairs selected for rail travel time calibration on a map, along with the percentage increase for each city pair from Railway Routing's theoretical travel time to the current timetable (as retrieved on various dates in various months of 2024). These differences vary from 0.0% (Krakow-Warsaw, from 2h20 to 2h20) to 45.9% (Umea-Stockholm, from 4h15 to 6h12). A table of these calibration city pairs is provided in Appendix A.2.

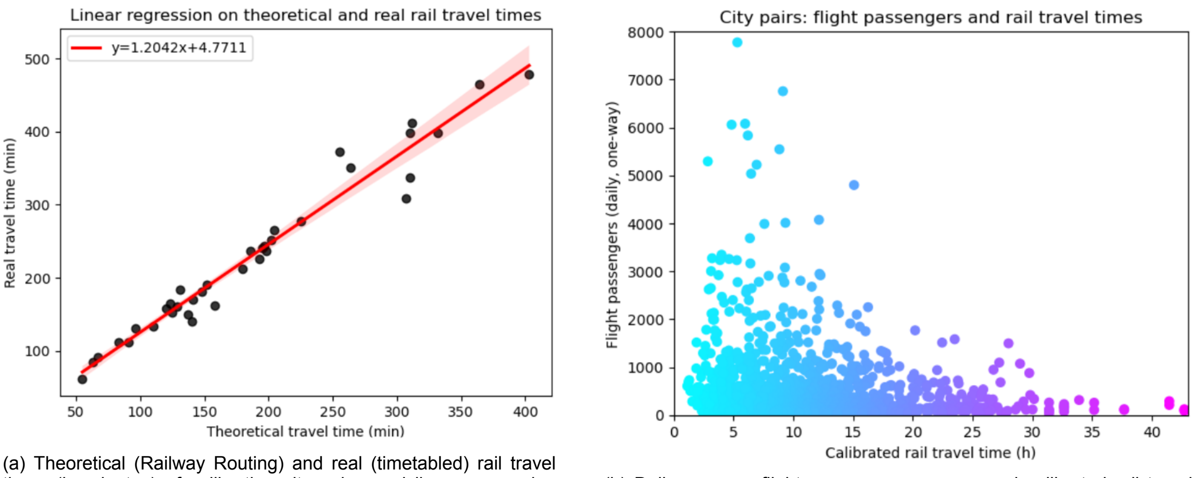
Figure 3.7a shows the Railway Routing and timetabled travel times for these city pairs. Considering the general outline of these data points, a linear trend can be identified. A linear least-squares regression model has thus been fitted on these data points in order to obtain a calibration formula. When rounding to three significant figures (considering the longest travel times considered here are in the order of three-digit minute values), this yields the following formula: $Calib(tt_{rail}) = 1.20 * tt_{rail} + 4.77$, with tt_{rail} measured in minutes. This result has an R^2 of 0.961, indicating that the calibrated rail travel times according to this regression model explain the timetabled travel times very well (on a scale from $R^2 = 0$ having zero explanatory value to $R^2 = 1$ having perfect explanatory value). The standard error is equal to 0.0416 minutes, implying a high precision considering (timetabled) travel times are



(a) All cities in the scope area of this research.

(b) City pairs used for rail travel time calibration, with percentage increase from theoretical (Railway Routing) to current (timetabled) travel time.

Figure 3.6: Overview maps of scope area and rail travel time calibration.



(a) Theoretical (Railway Routing) and real (timetabled) rail travel times (in minutes) of calibration city pairs, and linear regression model fitted on this data.

(b) Daily one-way flight passenger averages and calibrated rail travel times (in hours) for all city pairs.

Figure 3.7: Determination of rail travel time calibration formula and application to city pairs.

commonly measured in full minutes.

When measured by calibrated rail travel time, the distances of city pairs range from 1h11 (Rome-Naples) to approximately 41 hours (Bergen-Malaga). Figure 3.7b gives an impression of the distribution of these city pairs over their rail travel times. The 8 city pairs with the longest rail travel time all concern journeys to/from Norway.

3.6. Summary of methodology

For a clear and concise overview of the methodology steps that will be used to obtain the results in the next chapter, this section provides a summary of this chapter.

Figure 3.8 summarises the calculations performed in order to estimate night train demand.

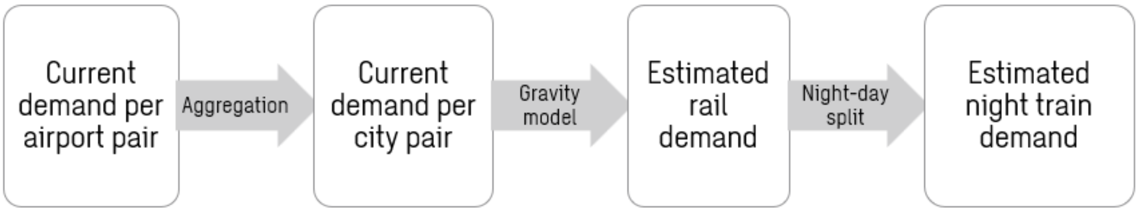


Figure 3.8: A flowchart summarising the process of night train demand estimation.

The complete calculation of this demand for a given city pair, consists of a gravity model combined with a novel function determining the night train's share of total estimated rail demand. This **simple night train demand formula** is as follows:

$$D_{NT} = DemandMutation * NightShare$$
$$= D_{air} * (1 - e_{tt} * (\frac{TotalTime_{air}}{TotalTime_{rail}} - 1)) * min(\frac{max(TotalTime_{rail} - MinNightTravelTime), 0)}{MaxDayTravelTime - MinNightTravelTime}, 1)$$

in which:

- D_{NT} represents the estimated night train demand on the city pair;
- D_{air} represents the current flight passenger volume between all airports of these two cities;
- e_{tt} represents the travel time elasticity of demand;
- $TotalTime$ represents the total travel time (including access/egress and idle times) of a mode;
- $MinNightTravelTime$ represents the minimum total travel time (including access and egress time) required for night train demand to exist on a city pair, i.e., below this threshold the demand share of night train is 0%;
- $MaxDayTravelTime$ represents the maximum total travel time (including access and egress time) for which day train demand exists, i.e., above this threshold the demand share of night train is 100%.

When the $DemandMutation$ component of the formula is applied to daily one-way passenger numbers on city pairs, it is referred to as the **full Estimated Daily One-way Demand (full ED1D)**.

The **applied night train demand formula**, inputting all parameter values and the calibration function of rail travel times as computed for this case study, is as follows:

$$D_{NT} = D_{air} * (1 + 1.0 * (\frac{tt_{air}/60 + 4}{0.2 * tt_{rail} + 1.0795} - 1)) * min(\frac{max(0.2 * tt_{rail} + 5.9205), 0)}{8}, 1)$$

with travel times (tt) measured in minutes. When this formula is applied to daily one-way passenger numbers on city pairs, it is referred to as the **night train Estimated Daily One-way Demand (night train ED1D)**.

Figure 3.9 summarises the methodology used in this research, outlining which research question concerns which parts of the methodology in particular.

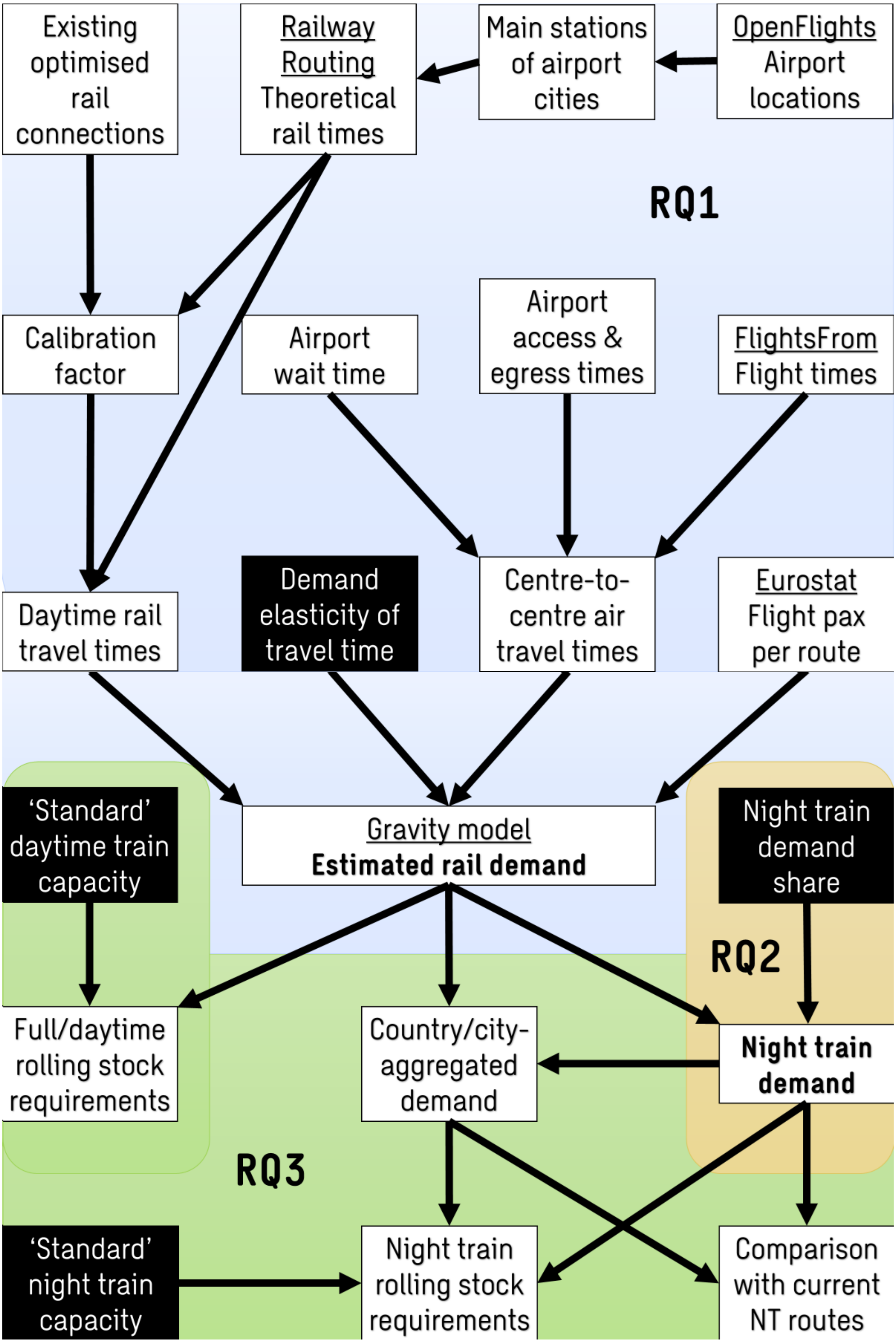


Figure 3.9: A flowchart of the research plan, with shaded backgrounds indicating the main areas of each research question. Black-shaded cells refer to RQ4 additionally to the other research question in whose area they lie.

4 Results

This chapter describes the results of the research executed according to the research plan (as described in Chapter 3) in order to answer the research questions. Each section describes a part of the results as well as the accompanying operational and performance indicators.

Unless specifically stated otherwise, demand values mentioned in the results concern the **full Estimated Daily One-way Demand (full ED1D)** as described in Section 3.3.1, and the **night train Estimated Daily One-way Demand (night train ED1D)** as described in Section 3.3.2. These values only concern the estimated additional rail demand resulting from maximum air-rail substitution and do not include any existing rail passenger numbers. Rail travel times mentioned in the results are the calibrated values and do not include access and egress time to and from the station, unless specifically stated otherwise. Values in the order of 10,000 or larger are rounded to thousands for readability.

The full table of calibrated rail travel times and demand estimations for each city pair is provided in Appendix A.3. The code used to generate the results is provided in Appendix A.4.

4.1. Demand estimation

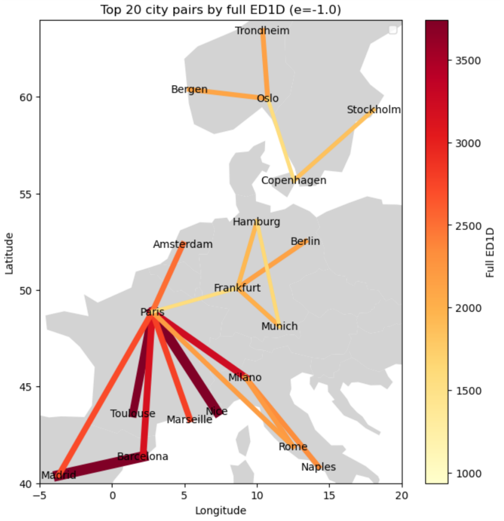
This section describes the main results of the demand estimation process, both for full and night train demand, along with the accompanying operational and performance indicators. The complete results for all 1,323 city pairs are provided in Appendix A.3.

4.1.1. Full demand

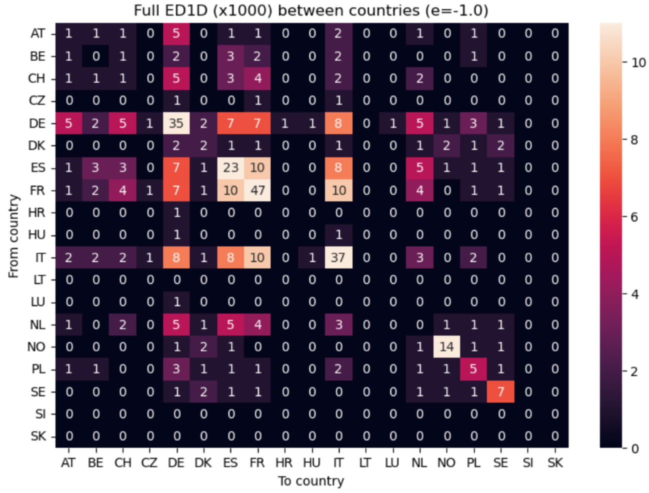
Given the selected demand elasticity of -1.0 (Börjesson, 2014) and the RTTs calculated using the calibration formula described in Section 3.5.1, the total ED1D over all city pairs becomes 237,000. This equates to 67.8% of total daily one-way air travel passengers, indicating that 113,000 daily one-way passengers (32.2%) choose to travel to a different destination (outside the cities in scope) and/or by a different mode, or not at all.

Figure 4.1a shows the twenty most popular city pairs by full ED1D. These city pairs are shown as lines on a map, with darker colours and thicker lines indicating a higher estimated demand. The map shows a large share of the top twenty city pairs by full ED1D radiating out of Paris, both for relatively short (Amsterdam and Frankfurt) and long (Madrid, Rome) distances, both for domestic (e.g., Nice and Toulouse) and international (Netherlands, Germany, Italy, Spain) destinations. For city pairs not connected to Paris, several popular domestic routes are shown: Madrid-Barcelona in Spain, Milan-Rome/Naples in Italy, several in Germany, Oslo-Bergen/Trondheim in Norway. Excluding Paris routes, Copenhagen-Stockholm and Copenhagen-Oslo are the most popular international routes by full ED1D.

Table 4.1 (left-hand side) lists the top ten city pairs by full ED1D, which together represents 10.5% of the entire demand. The table shows Barcelona-Madrid and Nice-Paris as clear leading city pairs by full ED1D, followed at some distance by Toulouse-Paris. The most popular city pair, Barcelona-Madrid, is additionally the shortest city pair in the top ten, with a rail travel time under three hours. This indicates a high potential demand between two cities connected by a near-continuous high speed line. The same holds for Milan-Rome, in tenth place the only other city pair in the top ten with a rail travel time under three hours. The longest city pair in the top ten is Madrid-Paris, with a travel time of almost nine hours



(a) Top 20 city pairs by full Estimated Daily One-way Demand (ED1D). Darker line colours and thicker lines indicate higher demand.



(b) Country pair-level aggregated full Estimated Daily One-way Demand (ED1D), in thousands of passengers, rounded to thousands.

Figure 4.1: Full estimated rail demand from maximum air-rail substitution, described by map of top 20 most popular city pairs and heatmap of country pair-level aggregated demand.

Rank	City pair	Full ED1D	Rail travel time	Rank	City	Full ED1D
1	Barcelona-Madrid	3,743	2h50	1	Paris	43,060
2	Nice-Paris	3,493	5h12	2	Frankfurt	25,258
3	Toulouse-Paris	2,818	4h44	3	Barcelona	22,997
4	Paris-Milan	2,469	5h49	4	Amsterdam	21,424
5	Barcelona-Paris	2,418	6h02	5	Madrid	19,479
6	Marseille-Paris	2,165	3h10	6	Rome	18,726
7	Madrid-Paris	2,124	8h51	7	Munich	18,674
8	Amsterdam-Paris	1,988	3h05	8	Milan	15,804
9	Milan-Naples	1,871	3h56	9	Zurich	12,111
10	Milan-Rome	1,785	2h55	10	Vienna	12,035

Table 4.1: Top 10 city pairs and cities by full Estimated Daily One-way Demand (ED1D).

on a route covered largely by high speed line, indicating that long travel times need not be a deterrent for rail travel demand. Overall, all city pairs in the top ten are connected by high speed lines for the majority of their route, implying this - with the model setup of this thesis - to be an important component for significant air-rail substitution demand potential.

From the figure and table, it becomes tentatively apparent that Paris is the source of a relatively large part of the demand: seven city pairs in the top ten are to/from Paris. This is confirmed by the **city-level aggregated demand** (introduced in Section 3.4.3), as shown in Table 4.1 (right-hand side) showing the top ten cities by aggregated full ED1D. Here, Paris is a clear leader as most popular origin/destination for estimated full rail demand - ED1D 43,000 over all city pairs to/from Paris, or 18.1% of total ED1D - followed at a considerable distance by Frankfurt and Barcelona.

Figure 4.1b shows the full ED1D by **country pair-level aggregated demand** (introduced in Section 3.4.3). This heatmap shows for each pair of countries the aggregated estimated full demand between them, with the full ED1D expressed in thousands. It becomes apparent that the four highest country-to-country relations all concern domestic travel: within France (ED1D 47,000), Italy (37,000), Germany (35,000) and Norway (14,000). The international relations with the highest estimated demand are France-Spain and France-Italy (ED1D 10,000 each), followed by Italy-Germany and Italy-Spain (8,000 each). For most other countries, Germany is the most popular international destination, along with Spain (for, e.g., Belgium) and Denmark (for Norway and Sweden), the latter finding implying the prevalence of travel demand between Scandinavian countries.

In line with the methodology described in Section 3.4.2, multiplying each travelling passenger with the calibrated rail travel time of their city pair yields a total of 1,754,000 daily **passenger hours** each way. Using the formula for $RollingStockNeeded$ as described in that section, this results in a need for an additional seat capacity of 219,000 on the railway network within the scope area. This is subject to the assumptions that no spare seat capacity exists on rail services already operating, that demand is distributed optimally and the additional rolling stock can be scheduled such that each seat is occupied for 16 hours every day. For scale, Table 4.2 shows what quantities of different types of existing rolling stock would be equivalent to these 219,000 seats.

Seat capacity	Rolling stock type	Quantity needed	Constructed quantity
439	DB Baureihe 408 / ICE 3neo trainset	500	90 ordered
510-556	SNCF TGV 2N2 / Euroduplex trainset	395-430	134
80	DB Bpmz / UIC-Z carriage	2,741	540

Table 4.2: Approximate equivalent of rolling stock quantity required to serve the estimated additional daytime rail demand (219,000 seats).

4.1.2. Night train demand

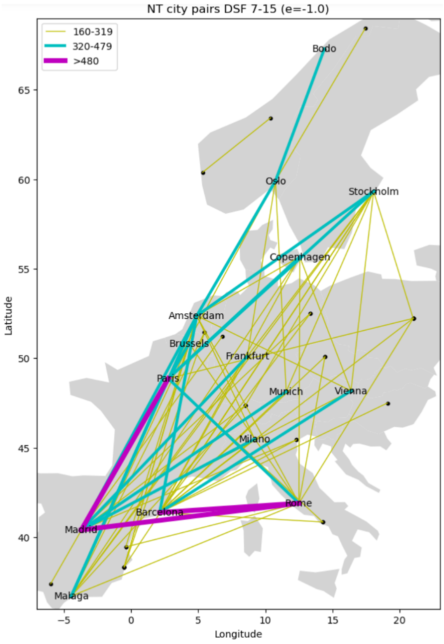
Given DSF 7-15 (the Demand Share Function with night train demand starting at 7 and daytime train demand ending at 15 hours of calibrated rail travel time), as described in Section 3.3.2, the night train ED1D over all city pairs becomes 47,000. This equates to 13.8% of original daily one-way air travel demand and 20.0% of the full ED1D from air-rail substitution.

Figure 4.2a shows all 69 city pairs with a night train ED1D above 160, which is 50% of the capacity of one Nightjet set or its full sleeping berth capacity. The map distinguishes three categories of city pairs depending on the load factor they would impose on a Nightjet set: 50-100% or 160-320 ED1D (in yellow), 100-150% or 320-480 ED1D (in blue), and >150% or >480 ED1D (in pink). Cities with at least one city pair over 320 ED1D are labelled with their name. The map shows Barcelona-Rome, Madrid-Rome and Madrid-Paris in the highest category as most popular city pairs by night train ED1D. For the city pairs above 320 ED1D (Nightjet load factor of 100%), most concern routes to/from Spanish cities: either Madrid, Barcelona or (on one occasion) Malaga. The only city pairs above this threshold not to/from Spain are Paris-Rome/Copenhagen/Stockholm, Amsterdam-Stockholm/Oslo and Oslo-Bodo. The vast majority of city pairs above this threshold are oriented from northeast to southwest, the only exceptions being Madrid/Barcelona-Rome (west-east) and Paris-Rome (northwest-southeast). Lithuania (Kaunas only), Slovakia, Slovenia, Croatia and Luxembourg all have zero city pairs with a night train ED1D above 160.

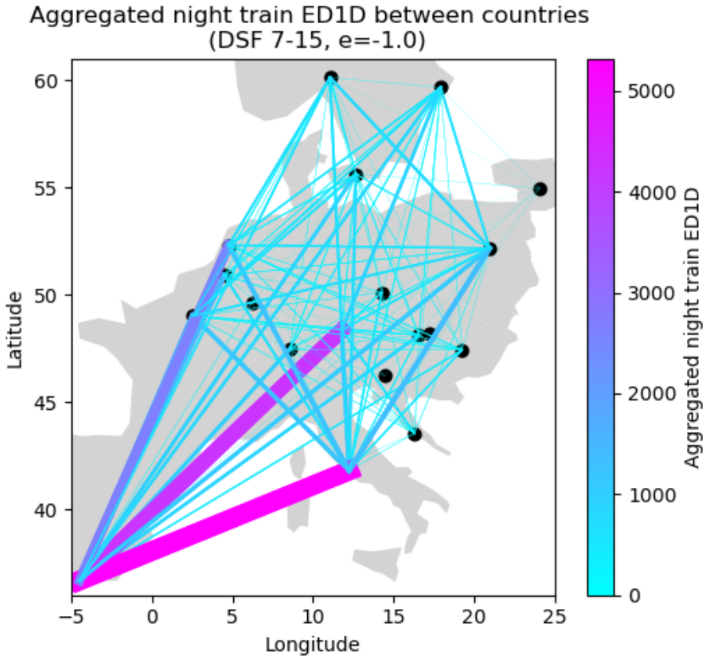
Table 4.3 (left-hand side) lists the top 10 city pairs estimated to be most popular for night train travel. Together, this top 10 represents 10.3% of the entire night train demand. From the figure and table, it becomes immediately apparent that Madrid-Rome is, by a clear margin, estimated as the city pair with the highest potential for a night train, with a night train ED1D of 958; this is equivalent to 3 Nightjet sets every night each way, with all sleeping berths and virtually all seats filled. Barcelona-Rome, having an overlapping trajectory with Madrid-Rome on its entire route, is in second place with a night train ED1D of 560 (1.75 Nightjet sets every night each way). The right-hand side of the table lists the top ten cities by **city-level aggregated demand** (introduced in Section 3.4.3), showing Madrid as top origin/destination for night train demand - night train ED1D 6,421 or 13.6% of total night train demand - followed by Amsterdam and Barcelona.

Regarding operational and performance indicators, if the entire night train ED1D of 47,000 were distributed such that it could be satisfied entirely with rolling stock with a load factor of 100%, and considering that services would operate both ways every night, this would require the introduction of the following approximate quantity of night train rolling stock:

- 296 new Nightjet trainsets (with a capacity of 320 passengers);
- or 2,631 classic sleeping carriages (with a capacity of 36 passengers);
- or 1,754 classic couchette carriages (with a capacity of 54 passengers).



(a) City pairs where estimated night train demand can fill at least half a Nightjet (or 160 spaces) every night each way, under Demand Share Function (DSF) 7-15.



(b) Country pair-level aggregated demand for night trains, expressed in Estimated Daily One-way Demand (night train ED1D), under Demand Share Function (DSF) 7-15.

Figure 4.2: Night train demand described by maps of key city pairs and country pair-level aggregated demand.

Rank	City pair	Night train ED1D	Rail travel time	Rank	City	Night train ED1D
1	Madrid-Rome	958	14h33	1	Madrid	6,421
2	Barcelona-Rome	560	11h44	2	Amsterdam	5,264
3	Madrid-Paris	491	8h51	3	Barcelona	4,907
4	Amsterdam-Malaga	467	14h46	4	Rome	4,770
5	Amsterdam-Milan	465	11h52	5	Malaga	4,703
6	Madrid-Milan	428	11h47	6	Paris	3,894
7	Munich-Madrid	416	13h12	7	Stockholm	3,877
8	Bodo-Oslo	376	15h40	8	Copenhagen	3,842
9	Frankfurt-Madrid	375	11h42	9	Oslo	3,280
10	Barcelona-Vienna	368	14h15	10	Warsaw	2,869

Table 4.3: Top 10 city pairs and cities by night train Estimated Daily One-way Demand (ED1D), under Demand Share Function (DSF) 7-15.

For Nightjet trainsets, this would imply a nine-fold increase compared to the current order quantity of 33 trainsets placed by ÖBB (ÖBB, 2023).

Table 4.4 provides statistics on the city pairs in six brackets of night train ED1D, based on their degree of occupancy of a new Nightjet trainset, used as baseline for night train rolling stock capacity as discussed in Section 3.4.1. This gives insight in the distribution of city pair demand. The largest portion of city pairs is shown to reside in the bracket of very small demand (1-39 ED1D). The range of rail travel times increases when the brackets' ED1D decrease, from 8-16h for the highest bracket to 7-41h for the lowest non-zero bracket, although it must be noted that this trend is in parallel with an increase of the number of city pairs in the brackets (increasing from 18 to 602, respectively). Even routes with a rail travel time above 24 hours are shown to have significant estimated night train demand from maximum air-rail substitution, as shown by the example of Stockholm-Malaga with a travel time of 27 hours and an ED1D of 223, sufficient to fill 70% of a Nightjet set.

Figure 4.3 shows the aggregated number of Nightjet sets that would be required to fill the total night train ED1D between each pair of countries. As an example: when the ED1D of all city pairs between Spanish and Italian cities is combined, this aggregated demand is sufficient to fill approximately 17

Category	1	2	3	4	5	6
ED1D bracket	320+	160-319	80-159	40-79	1-39	0
Nightjet load factor	>100%	50-100%	25-50%	12.5-25%	0-12.5%	0%
No. of city pairs	18	51	102	155	602	395
Total night train ED1D	7,632	10,623	11,227	8,659	9,385	0
Longest city pair (ED1D|RTT)	Bodo-Oslo 361 | 15h40	Stockholm-Malaga 223 | 26h56	Oslo-Malaga 121 | 28h36	Bergen-Gdansk 41 | 28h41	Stavanger-Malaga 8 | 41h01	Cologne-Bayonne 0 | 7h15
Shortest city pair (ED1D|RTT)	Paris-Rome 347 | 8h34	Amsterdam-Milan 190 | 8h49	Paris-Venice 84 | 7h42	Oslo-Stavanger 54 | 7h22	Berlin-Zurich 5 | 7h04	Rome-Naples 0 | 1h11

Table 4.4: Summary statistics on six categories of city pairs determined by their night train Estimated Daily One-way Demand (ED1D) bracket.

Nightjet sets departing from Spain to Italy every night (as well as 17 in the opposite direction). Figure 4.2b visualises the size of these aggregated night train demand flows for international country relations, showing very clearly the most popular international connections leading to/from Spain with significantly higher estimated demand than between almost all other countries, primarily in Spain's connections with Italy, Germany and Netherlands.

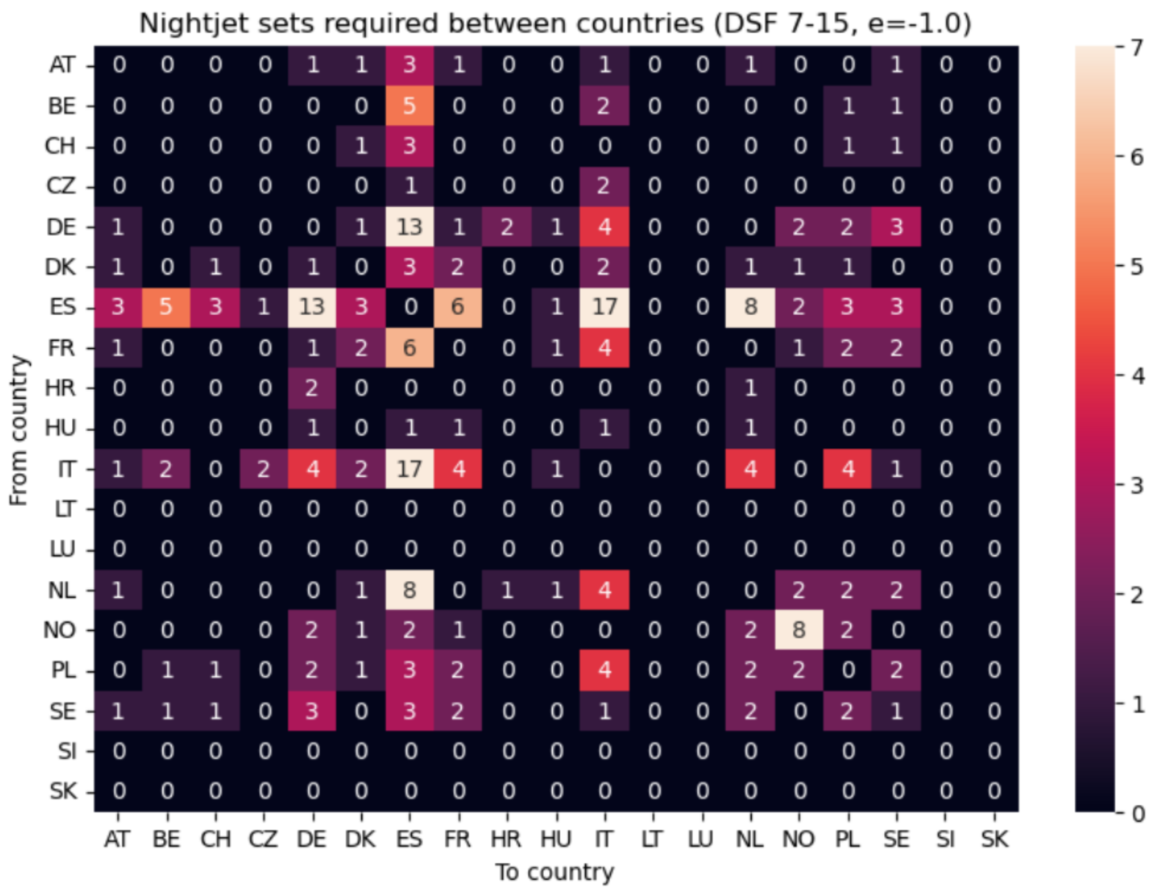


Figure 4.3: Number of Nightjet sets (capacity 320) required to fill the total night train Estimated Daily One-way Demand (ED1D) between countries, under Demand Share Function (DSF) 7-15.

Figure 4.3 shows that for 9 out of 19 countries, Spain is the destination with highest night train demand. The exceptions to this rule are:

- Italy, most popular destination from Czechia, Spain, Hungary, Poland and Slovakia;
- Germany, most popular destination from Croatia and Sweden;
- Denmark, most popular destination from Lithuania (Kaunas only);
- Norway, most popular destination from Norway itself;
- France, most popular destination from Slovenia.

As an example of the implications of these outcomes for a specific country, Table 4.5 shows the total combined night train ED1D from all Dutch cities (Amsterdam, Rotterdam, Eindhoven and Maastricht), grouped by destination country. Roughly geographically aggregated, over 8 Nightjet sets could be filled with demand in the direction of Spain, 4 towards Italy (plus Nice), 2 towards Austria and beyond (Slovenia, Croatia, Hungary), 2 towards the direction of Czechia and Poland, and almost 5 towards Denmark and beyond (Sweden, Norway).

Country	**Total night train ED1D**	**Nightjet sets**	**Cities**
Spain	2,645	8.27	Malaga (777), Alicante (563), Madrid (486), Barcelona (382), Valencia (282), Sevilla (145), Gerona (10)
France	79	0.25	Nice (62), Toulouse (17)
Italy	1,235	3.86	Rome (277), Milan (189), Venice (130), Naples (119), Florence (81), Bologna (77), Pisa (77), Bari (62), Bergamo (37), Brindisi (34), Villafranca (19), Treviso (12), Genoa (11), Turin (10)
Austria	230	0.72	Vienna (200), Graz (15), Innsbruck (8), Salzburg (7)
Slovenia	17	0.05	Ljubljana (17)
Croatia	195	0.61	Zagreb (108), Split (80), Pula (10), Rijeka (7)
Hungary	259	0.81	Budapest (242), Debrecen (17)
Czechia	123	0.38	Prague (123)
Slovakia	8	0.03	Bratislava (8)
Poland	536	1.68	Warsaw (205), Krakow (159), Gdansk (99), Katowice (42), Wroclaw (28), Poznan (3)
Denmark	334	1.04	Copenhagen (224), Aalborg (55), Billund (55)
Sweden	502	1.57	Stockholm (357), Gothenburg (102), Linköping (43)
Norway	628	1.96	Oslo (335), Bergen (101), Stavanger (68), Trondheim (54), Sandefjord (37), Kristiansand (33)

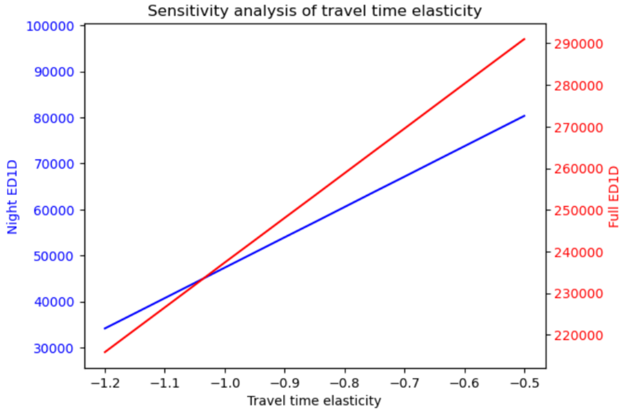
Table 4.5: Overview of all night train Estimated Daily One-way Demand (ED1D) from Dutch cities, counterclockwise by partner country with non-zero night train demand, under Demand Share Function (DSF) 7-15.

4.2. Changing input parameters

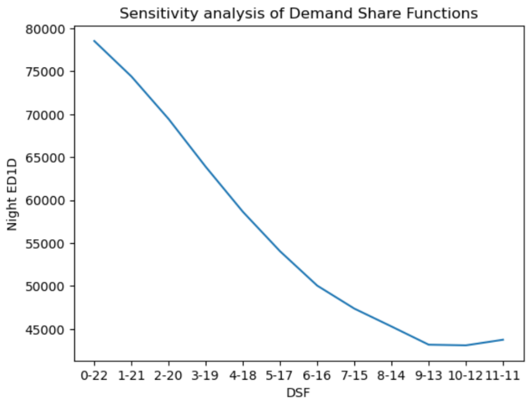
This section describes how key input parameters were altered in additional scenarios to test their influence.

4.2.1. Travel time elasticity

For comparison of travel time elasticity values, a range of values is tested from -0.50 to -1.20 in increments of 0.05. Figure 4.4a shows the effect of varying the elasticity value on the total ED1D over all city pairs, for both the full and night train demand. A perfectly linear pattern is observed, with the full ED1D increasing by approximately 5,400 and the night train ED1D by 3,300 for each elasticity increment of 0.05. Wardman (2012)'s -0.65 for inter-urban travel leads to a total ED1D over all city pairs of 275,000, an increase of 15.8% compared to the baseline -1.0 elasticity value.



(a) Sum of all Estimated Daily One-way Demand (ED1D) for different travel time elasticity values, for both full and night train ED1D. Ceteris paribus, under Demand Share Function (DSF) 7-15.



(b) Sum of night train Estimated Daily One-way Demand (ED1D) for different Demand Share Functions. (Ceteris paribus.)

Figure 4.4: Sensitivity analysis of travel time elasticity and Demand Share Functions.

4.2.2. Demand Share Function

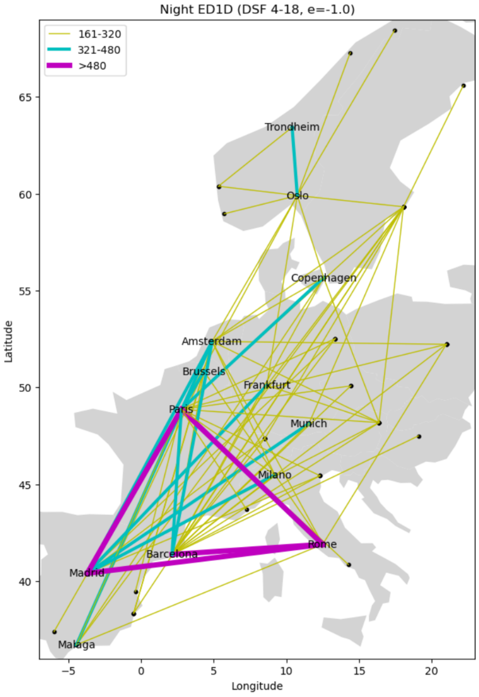
For comparison of Demand Share Functions (DSFs), a range of DSFs is tested from 0-22 to 11-11, with the minimum time for night train demand incrementing by 1 hour and the maximum time for daytime train demand reducing by 1 hour with every step. Figure 4.4b shows the effect of varying the DSF on the total night train ED1D over all city pairs. It becomes apparent that the DSF has a strong influence on the total ED1D, varying from 78,541 (DSF 0-22) to 43,088 (DSF 10-12). Generally, the lower the minimum threshold for night train demand to exist, the higher the total demand, despite the maximum threshold for daytime travel demand simultaneously moving in the opposite direction. (The only exception is DSF 11-11, where night train demand is 0% below and 100% above 11 hours of rail travel time.) This can be explained by the general trend of fewer and less popular city pairs occurring with increasing rail travel time, as has been hinted at in Figure 3.7b. The city pairs with the highest demand tend to be in the shorter range of travel times, thus impacting the total demand across all city pairs stronger when they (are about to) lose night train demand share.

An interesting alternative DSF to highlight is based on the currently existing night train connection with the shortest end-to-end calibrated rail travel time. This is Malmö-Stockholm, with a rail travel time of 4h10, coincidentally equal to the current shortest timetabled service on this route. For this alternative DSF, it is assumed that there must be a non-zero night train demand estimated by the model on this connection. This leads to a DSF with night train demand starting at 4 hours of rail travel time. In line with the active hours principle, and taking into account the one hour of rail access and egress time, this implies that there would be 5 inactive hours and 19 active hours in a day, and subsequently a maximum of 18 hours of rail travel time for daytime rail travel demand. Therefore, DSF 4-18 is applied to the dataset as an alternative. Under DSF 4-18, the total night train ED1D across all city pairs is 59,000, an increase of 23.9% compared to the baseline DSF 7-15.

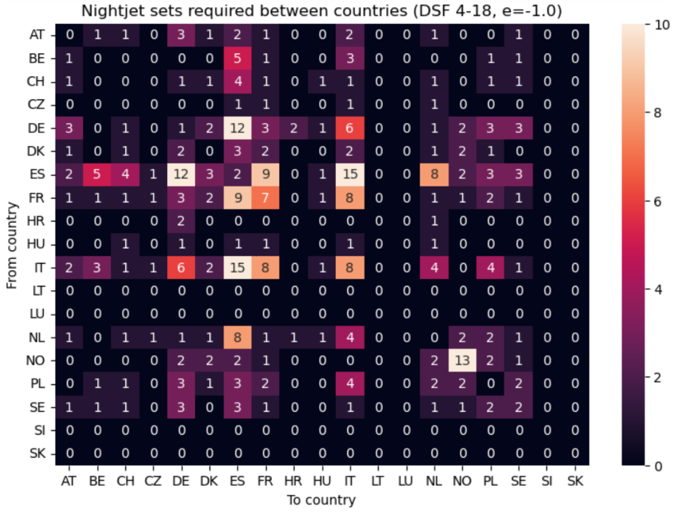
For illustration, Figure 4.5a shows all 75 city pairs with a night train ED1D over 160 under this alternative DSF 4-18. Only a net six more city pairs now fall above this threshold; the general outline of the map is unchanged. Figure 4.5b shows the country-level aggregation results expressed in Nightjet sets under DSF 4-18. Spain-Italy is still the main country relation, now with 15 daily Nightjet sets each way, but domestic travel in Norway has leapt to second place (13 sets), followed by Spain-Germany (12 sets). Italy (8 sets) and France (7 sets) now show significant domestic night train demand estimations too, as do Sweden and Spain (each 2 sets' worth of demand).

4.3. Summary of results

A total 237,000 daily passengers each way are estimated as full demand (i.e., for daytime and night train demand together) from maximum air-rail substitution, meaning 1 in 3 current air passengers would choose to not travel or travel elsewhere. Of all cities, Paris is the strongest generator of full demand, good for 43,000 daily passengers each way in all directions combined, followed by Frankfurt and Barcelona. Satisfying the full demand is roughly estimated to require 219,000 additional seats on



(a) City pairs where estimated night train demand can fill at least 160 spaces (equivalent to 50% of a Nightjet set or all of its sleeping berths) each way every night under the alternative Demand Share Function (DSF) 4-18.



(b) Number of Nightjet sets (capacity 320) required to satisfy the total estimated night train demand each way between countries under the alternative Demand Share Function (DSF) 4-18.

Figure 4.5: Overview map and heatmap for alternative Demand Share Function (DSF) 4-18.

the network, equivalent to several hundreds of high-speed trainsets or a few thousand carriages.

Daily night train demand from maximum air-rail substitution is estimated at 47,000 each way under Demand Share Function (DSF) 7-15, equivalent to several hundred new Nightjet trainsets or a few thousand classic carriages. Madrid-Rome and Barcelona-Rome are the city pairs with highest night train demand, and nine of the top ten night train city pairs are to/from Spain. Of all cities, Madrid has the highest night train demand in all directions combined (6,000 daily each way), followed by Amsterdam and Barcelona. When aggregated by country, Spain has the highest night train demand as origin/destination (estimated at a total of 68 Nightjets each way per night), followed by Italy and Germany; Spain-Italy is the country relation with highest night train demand, followed by Spain-Germany and Spain-Netherlands. Generally, most city pairs with high night train demand are oriented northeast-to-southwest.

Changing the value of travel time elasticity has a linear effect, with a 15.8% higher demand observed under a value of -0.65 compared to the baseline -1.0. Demand share functions where the range of mixed daytime/nighttime travel is wider (but centred around the same midpoint) generally estimate higher night train demand. Demand Share Function (DSF) 4-18 (based on the shortest currently existing night train connection, Malmö-Stockholm) has a 23.9% higher night train demand estimate (59,000) than the baseline DSF 7-15, and highlights increased shorter-distance night travel demand, especially for domestic overnight travel in, e.g., Norway.

The next chapter will further elaborate on the implications of these observed results.

5
Discussion

This chapter discusses the policy implications of the results as shown in the previous chapter and elaborates on the limitations of the applied methodology.

5.1. Policy implications

This section interprets the results and uses these to formulate policy recommendations.

5.1.1. Effects of implementation

As described in Chapter 1, air-rail substitution has considerable potential to achieve greenhouse gas emission reduction. However, for earlier air-rail substitution proposals, it has been noted that emission reduction effects may be smaller than expected - if not marginal - for several reasons: demand only shifting to rail partially, increased rail transport emissions (albeit lower than those of air transport), and the opposite effect of current air travel growth cancelling out substitution effects even on the scale of substitution up to 1200 km (van Goeverden, 2023). Although the scale of air-rail substitution evaluated in this thesis is larger than in earlier proposals and studies, these points are still relevant. If passenger air travel within the scope area is not banned entirely - e.g., on city pairs where the rail alternative is considered to be of insufficient quality or capacity - the remaining flights will continue to emit greenhouse gases. The same holds for flights outside the scope area, including intercontinental flights. Those remaining flights may even see an increase in demand due to the removal of flights competing for passengers with flexible destinations (e.g., leisure travellers) while the rail alternative takes (considerably) longer; a type of 'waterbed effect'. Furthermore, in case of substitution of short- and medium-haul flights (by a rail alternative, in this case), there is a risk that the airport slots becoming available as a result will be filled up with other flights, especially the more profitable long-haul flights, as was seen in the past when additional slot capacity was introduced (Dray, 2020). This would negate the entire effect of emission reduction through air-rail substitution and may directly increase emissions even without taking into account the natural growth of air travel. Therefore, in order to actually realise the emission reduction potential indicated by this thesis, solely improving the rail offer (by introducing the proposed additional daytime and night trains) will not suffice. Restrictions of air travel through policy measures are crucial to achieve this emission reduction.

Additionally to the environmental benefits mentioned before, the hypothetical scenario investigated in this study can become relevant in the event that airspace has to be closed for a longer time. This may happen for several reasons, such as a natural catastrophe. The 2010 eruption of the Eyjafjallajökull volcano in Iceland, closing airspace above most European countries for a week, proved that such events occur and can severely affect airspace availability (Budd et al., 2011). Another reason, which is becoming increasingly relevant in the current age, could be constituted by geopolitical developments such as a military threat to civilian airspace while rail traffic remains available, as is currently the case in Ukraine (Pape, 2022). Although these disturbances of airspace availability are of a more temporary nature than structural changes to long-distance transport networks for environmental reasons, they still constitute scenarios with an urgent need for substantial reduction of air traffic, and policy makers may desire to prepare for such events for resilience or strategic reasons, respectively. Although the primary objective of this thesis research is not to prepare for such events, it can still be usefully applied if they occur.

5.1.2. Greatest air-rail substitution potential

Exploratory analysis of full travel demand showed routes to/from Paris to have particularly high demand estimates in case of large-scale air-rail substitution. As for night train demand specifically, Spain has shown itself as a high-potential destination for night train services from a large part of Europe, with sufficient potential estimated for no fewer than 68 international night trains departing every night, each filled to near-capacity of 320 passengers. (Note that this demand only concerns the southeastern half of Spain directly accessible by normal-gauge railway from the rest of Europe.) Madrid-Barcelona-Milan-Rome is by far the night train corridor with greatest potential. More broadly, the most demand for night trains appears to be on routes oriented from northeast to southwest.

The high demand estimations to/from Spain may be explained by the country's strong pull on tourism, taking up the highest share (17.7%) of touristic overnight stays in the EU between member states (Eurostat, 2023c). Additionally, the country is located in a corner of the scope area, due to which distances and travel times to many countries are more likely to be long enough to yield a significant night train demand share, as opposed to more centrally located countries in Europe for which the average travel time to other destinations in the scope area is shorter.

These findings form a contrast with the current situation of night trains in the scope area in several ways. The top 51 city pairs by estimated night train demand are all not currently served by a direct night train; Amsterdam-Vienna is the existing connection with the highest estimated demand, ranked 52nd. Spain has no night trains whatsoever, barring French domestic night trains serving minor stations at the Spanish border (Maier, n.d.). Cross-border night trains (as opposed to domestic routes) make up a significantly smaller share of all night trains than would be expected from the demand estimation results, which showed only Norway and Sweden to have domestic night train potential; admittedly, this concerns the estimations under DSF 7-15, and due to the shorter average length of domestic journeys compared to international ones, DSFs where night train demand starts at a shorter travel time (e.g., DSF 4-18) estimate more potential for domestic night trains. Current night train routes exist in a higher density in central and eastern Europe (Maier, n.d.), in contrast with demand estimations showing highest potential in the western part of the continent. Finally, a slight majority of current night trains appears to be oriented northwest-to-southeast (Maier, n.d.), opposing the finding of highest potential existing northeast-to-southwest.

This indicates that border crossings form a barrier for night train operations, in confirmation of earlier findings by Donners (2016) and Odendahl (2020); that night train transport is under-prioritised in western European countries; and that routes oriented northeast-to-southwest are underdeveloped compared to northwest-to-southeast routes.

5.1.3. The case for high-speed night train development

The new Nightjet trainsets have a maximum operational speed of 230 km/h (ÖBB, 2023). This is significantly lower than the maximum line speed of most high-speed lines (300-320 km/h), causing a decrease in line capacity when night trains run mixed with high speed trains. This is not necessarily a problem when line frequencies are comparatively low, night trains operate outside peak hours (e.g., during nighttime) or conventional railway lines exist as an alternative. However, an issue arises in the case of Spain: the only normal-gauge railway accessing the cities in the scope area is a set of high-speed lines. All night trains reaching further into Spain than Barcelona would be forced to use the heavily-used Barcelona-Madrid high-speed line, and with Spain being the origin/destination rather than a pass-through country, night trains would use the line during daytime, potentially during morning and evening peak hours.

In order to avoid this issue, the development of high-speed night train rolling stock is proposed as a policy recommendation. For Spain alone, where high-speed night trains would be the most but not exclusively useful, 68 trainsets with a length of approximately 200 metres have been estimated to be viable to fill to capacity every night in each direction, amounting to 136 trainsets required to operate in both directions. This is an indication that high-speed night train rolling stock could be in high demand if it were developed, with the concept of economies of scale thus potentially improving the business case for development.

5.2. Limitations

This section describes the limitations of the approach used in this thesis, and the effects they may have on the outcome.

5.2.1. Rail travel times

Depending on the time of inquiry and the tool, website or app used to find current rail travel times, different results are possible. While Direkt Bahn Guru uses "a (legacy) API by Deutsche Bahn to find all direct trains running via a given station within the next 1-2 weeks" (Tens, n.d.), its results are occasionally in conflict with a direct inquiry via the Deutsche Bahn app mere hours or days ahead, which then shows itineraries with shorter direct travel times than those shown by Direkt Bahn Guru. Chronotrains states it is "using data from the Deutsche Bahn through Direkt Bahn Guru" to calculate rail travel times between any two stations based on current timetables, including transfer times (Chronotrains, n.d.), and yet its results occasionally differ from those of Direkt Bahn Guru on direct connections.

Additionally, both Direkt Bahn Guru, Chronotrains and HAFAS suffer from a common reliability issue regarding their use for this thesis: the fastest rail option on a route will not appear in journey planners if it is temporarily cancelled, rerouted and/or slowed down due to track works or other reasons. During the data collection process of current rail travel times, the above sources were consulted multiple times across several months (between March and August 2024) and some connections saw a variety of travel time outcomes across these sampling moments. In case of such variety, the shortest travel time across all of these sampling moments was used.

With the use of more rail timetable data sources and more sampling moments, lower minimum values for travel times on rail routes may have been found. This would have led to a calibration function with less buffer time added to Railway Routing's calculated theoretical times, thus to lower calibrated rail travel times and eventually to higher estimates for rail demand.

Furthermore, regarding scope decisions (as described in Section 1.4) affecting the calculation of travel times, the inclusion of more temporary track works effects would have increased rail travel times and thus decreased estimated rail demand. On the other hand, the inclusion of future rail infrastructure and timetable improvements would have had the opposite effect: shorter rail travel times leading to higher rail demand estimates.

5.2.2. Rail travel time calibration

The criteria of 'optimised' city pairs to be included in the calibration dataset have not been verified. These calibration routes have also been selected manually without full guarantee that these are a balanced mix of timetabled rail connections to formulate a calibration function, and without full guarantee that these routes follow the criteria of 'optimised' city pairs. As described in Section 5.2.1, the timetabled travel times found may be higher than in reality as well.

Furthermore, the overall quality of the rail travel time calibration method applied in this thesis has not been verified. It is possible that better methods exist to determine realistic rail travel times across Europe, both with regard to better-supported methods and automation. The (not publicly disclosed) methods of determining optimised rail travel times used to carry out earlier studies (Wesdorp and Moerman, 2021; Durand and Romijn, 2023) may be of interest here.

5.2.3. Access/egress times

In order to remain consistent with Durand and Romijn (2023)'s fixed time supplements for airport idle times, as well as to reduce the (computational) workload and data collection efforts, the choice was made to apply fixed time supplements for access and egress times to/from airports and stations, as opposed to specific supplements, as was discussed in Section 3.2.2. A methodology including location-specific access/egress time supplements depending on distances or travel times between airports/stations and cities could provide more accurate centre-to-centre (or door-to-door) travel times, and thus improve city pair-specific predictions for the travel time-related change in travel demand upon air-rail substitution. This can be carried out in several ways, such as:

- by using great circle distances to geographical city centres or main landmarks in each city, as Donners (2016) did;
- by researching public transport or road travel times between airports/stations and geographical

city centres or main landmarks in each city;

- or by researching public transport or road travel times between airports and stations, if a simpler model is preferred using an assumption that railway stations are proxies for the city centres.

5.2.4. Air transfer passengers

For the Eurostat data as applied in this thesis, it is assumed that 100% of passengers recorded on a flight concern point-to-point origin-destination journeys from the flight origin to the flight destination. This does not take into account transfer passengers.

For transfer passengers to/from a point outside the scope area - e.g., intercontinental passengers - the (perception of) total travel time changes compared to point-to-point travel. On the one hand, access and egress time at the transfer airport would disappear, since the passenger does not need to travel outside the airport for their transfer. The same may hold for idle time, if airport regulations do not require a transfer passenger to pass through security procedures a second time if they have already done so at their origin airport. This would lead to a shorter air travel time and thus a stronger decline in demand on that city pair when air-rail substitution is put in place. On the other hand, the passenger's total journey time is longer than reflected by the air travel time calculated for their flight leg within the scope area, meaning that replacing that leg with a rail journey has a relatively smaller impact on their total journey time. This could, in turn, lead to a weaker decline in demand on the city pair within the scope area.

For transfer passengers whose entire journey lies within the scope area, their total air travel time on each flight leg is shorter due to the removal of access/egress and idle time at their transfer airport. However, their total air journey time from origin to destination is longer than it would have been on a direct flight. Without knowing the full routes of transfer passengers, it is difficult to draw conclusions on how their behaviour would change compared to point-to-point travellers.

5.2.5. Confidence level and validation of results

As shown in Section 4.2, altering assumptions on parameter values with little literary support (due to lack of available literature and/or other resources) leads to significantly differing outcomes in demand figures, with the total estimated demand changing up to 24% when the second-most preferable parameter settings are used, and even more strongly when other settings are considered as well. For this reason, the confidence level of precise demand estimation results is comparatively low. Therefore, the results of this thesis primarily serve an indicative purpose of the scale of desired additional railway services and rolling stock - i.e., do we need dozens, hundreds or thousands of additional trains? - as well as a comparative purpose, to identify which routes, corridors or countries have greater (night) train potential than others.

Furthermore, the results of this thesis cannot easily be validated, as the hypothetical scenario of maximum air-rail substitution has not been put into practice anywhere in the world, at least to the knowledge of the author. Using earlier studies on air-rail substitution potential as validation data is difficult, due to fundamental differences in assumptions and scale of substitution.

6 Conclusion

This chapter uses the findings from previous chapters to answer the research questions and provides suggestions for further research.

6.1. Answering the research questions

This thesis intended to find the maximum limit of demand potential for night trains in the hypothetical scenario of full air-rail substitution. For this purpose, the following main research question was identified: **On what routes in the continental Schengen area would night trains be required to enable maximum substitution of air travel?** This problem was tackled using the following four sub-questions (RQs):

1. *What is the expected maximum demand for rail travel between city pairs from air-rail substitution?*
   The total daily one-way demand across all city pairs was estimated at 237,000, two-thirds of original air passenger numbers, given a travel time elasticity of -1.0 (Börjesson, 2014). Barcelona-Madrid is the most popular city pair with 3,743 daily estimated passengers each way, followed by Nice-Paris and Toulouse-Paris. Paris is by far the most popular city with 43,000 daily estimated passengers in all directions each way, followed by Frankfurt and Barcelona.

2. *What is the expected maximum demand for night trains between city pairs from air-rail substitution?*
   The total daily one-way night train demand across all city pairs was estimated at 47,000, given the assumption that night train demand begins at 7 hours of rail travel time and daytime travel demand ends at 15 hours. This is equal to 14% of air passengers or 20% of estimated rail passengers. Madrid-Rome and Barcelona-Rome are the top 2 city pairs, with a combined 1,518 estimated daily night train passengers each way, followed by Madrid-Paris. Many popular city pairs are to/from Spain; generally, most city pairs estimated to be of significance to night train travel are oriented northeast-southwest. Madrid is the most popular city for night train demand, with 6,421 daily estimated passengers in all directions each way, followed by Amsterdam and Barcelona.

3. *What are the performance and operational implications of the resulting demand estimation?*
   Regarding full demand (not exclusively for night trains), satisfying the estimated total demand would require an additional seat capacity in the order of 400-500 high-speed trainsets or 3,000 carriages. Paris has the highest estimated air-rail substitution demand potential of all cities in the scope area, while Barcelona-Madrid is the most popular route by demand estimations. For satisfying the estimated night train demand, a few hundred additional Nightjet sets or a few thousand classic night train carriages would be needed. Spain has the highest estimated night train demand of all countries in the scope area and is the most popular destination for many other countries; Madrid-Rome and Barcelona-Rome are the most popular estimated night train routes for air-rail substitution potential.

4. *What variables have influence on the resulting network and to what extent?*
   Sensitivity analysis of travel time elasticity showed a linear effect on estimated demand, with daily one-way demand increasing by 5,400 in total and 3,300 for night trains with every increase of elasticity by 0.05. Sensitivity analysis of different functions of night train demand share of overall substitution rail demand using a common 50% share point showed higher demand estimations when the shift from daytime to nighttime travel was more gradual (starting at relatively short travel times); the effect on total night train demand was 82% higher under the most gradual shift scenarios than under one of the most abrupt shifts. In a scenario with a wider bandwidth of shared night/daytime rail demand, a function with night train demand starting at 4 and daytime train demand ending at 18 hours, shorter-distance and domestic routes in particular saw a demand increase, e.g., with a major increase in estimated demand potential for domestic night trains in Norway.

These partial answers allow to formulate an answer to the main research question. In the hypothetical scenario of maximum substitution of air travel by rail, night trains would most strongly be required on routes between Spain and the rest of Europe, with Madrid-Rome and Barcelona-Rome having the highest estimated demand, and in general primarily required on routes oriented between the northeast and the southwest of the continent. Overall, circa 14% of existing air passenger demand is estimated to switch to the night train (as opposed to daytime rail travel or choosing not to travel) when air routes are maximally substituted. Satisfying the total night train demand from maximum air-rail substitution would require the deployment of the equivalent of circa 300 Nightjet trainsets to serve the night train routes. However, the conclusions, and especially the numerical results, are significantly dependent on assumptions regarding traveller behaviour in the scenario of maximum air-rail substitution, such as the degree to which travellers choose to abstain from travelling when travel times increase, and travel time thresholds for night and daytime train usage.

6.2. Main recommendations

Given the findings in RQ2 and RQ3, the following policy recommendations are formulated for the further development and improvement of night train services in Europe:

- **Focus primarily on the introduction of international night trains to/from Spain, and secondarily Italy.** Although inland Spain is currently not served by any night trains, routes to and from Spain are shown to have the largest potential night train demand of all countries in the scope area, sufficient to fill up to several dozens of night train connections to and from Spain every night in the case of maximum air-rail substitution. The same holds for routes to and from Italy, which is runner-up in terms of potential night train demand behind Spain.

- **Work on the resolution of border barriers for long-distance (night) rail transport.** A significant share of currently existing night trains operates domestically or at relatively short distances, in contrast with the outcomes of this thesis showing a comparatively much higher demand for international, longer-distance routes. Resolving border barriers should allow the potential demand on those international routes to be served more optimally; daytime rail services would benefit from the resolution of such border barriers alongside night trains.

- **Improve the position of and attention for night train transport in western European countries.** While currently existing night trains operate more predominantly in the eastern part of the scope area (central Europe), this thesis has shown the most potential demand for night trains in western Europe, an area with few to no existing night trains depending on the country. This implies that night trains in western Europe receive insufficient attention and their weaker market position compared to eastern European countries is in imbalance with actual potential demand.

- **Focus on the introduction of northeast-to-southwest night train connections.** While currently existing night trains do not have a clear dominant geographical orientation, this thesis showed an overwhelming majority of city pairs with high potential demand for night trains to be oriented from northeast to southwest. This implies that night train routes in that direction have higher potential than the northwest-to-southeast routes which are currently already being served relatively frequently compared to their air-rail substitution potential.

The demand estimation model developed in this thesis, as well as its results, may be useful in several applications. The model itself can be applied in smaller-scale, more in-depth case studies of specific routes or areas in order to model the effect of flight substitution on rail demand and determine the required investments in railway infrastructure, rolling stock, logistics, policy etc. to properly allow for air-rail substitution, depending on the standards set by stakeholders in such case studies. Furthermore, the model can be applied to case studies on a similar scale with different parameters and base data, such as a demand estimation study specifically for certain seasons or periods of the year, rather than the entire year. The results, in particular the list of city pairs with their estimated full and night train demand, can form a basis for a more extensive study using city pair demand estimates to develop a concrete route network, be it for night trains or daytime rail services, comparing alternative routes, developing service patterns and timetables, determining stopping patterns, etc.

However, there exists a significant literature gap in the field of long-distance and night train travel behaviour, especially for scenarios where air travel is excluded as an option. Primarily this gap, as well as time and resource constraints in this thesis, have required the use of several assumptions that showed a strong effect on the quantitative outcome when associated input parameter values were altered. Furthermore, the step from demand estimations between cities to the formation of proposed night train routes remains to be bridged. All in all, this thesis provides an indication of the most interesting regions and corridors to further explore, and simultaneously points out the need for additional academic research to gain a full understanding of the exact scale of rail investments required to facilitate large-scale air-rail substitution.

6.3. Further research

This section provides suggestions for further research directions that could improve or expand on the methodology and results of this thesis, or reduce its limitations.

6.3.1. Travel behaviour under strong air-rail substitution

As seen in Chapter 2, little to no scientific literature exists regarding travel behaviour on long distances in general, and regarding travel behaviour in the scenario of large-scale air-rail substitution and subsequent removal of air connections specifically. For this reason, a variety of assumptions had to be made in order to carry out this thesis. Further research could investigate the nature of travel behaviour if the hypothetical scenario at hand in this thesis were to come true. Such research may concern factors such as destination choice, trip frequency, shifts to/from other (road-based) modes, and preferences between daytime and night travel (e.g., in terms of willingness to pay) for comfort and rail travel time. A Stated Preference survey similar to that of Weisshaar (2024) may be a good approach to uncover these behavioural aspects.

6.3.2. Access/egress and idle times

For a realistic impression of full-journey travel times, it is necessary to use access/egress times in some form, since stations and airports are virtually never the place of residence of travellers, nor is it usually their destination. As discussed in Section 3.2.2, this thesis uses generic access and egress times of two hours for air travel and one hour for rail travel, both for complexity and consistency reasons. However, as also discussed in Section 5.2.3, a location-specific method of determining access and egress times would lead to more precise travel time values, and thus more precise estimations of changes in travel demand. Further research into access and egress times could include approaches such as:

- applying Rothfeld et al. (2019)'s research approach to all airports in the case study;
- using Rothfeld et al. (2019)'s results to develop a predictor method for access and egress times for other airports based on similarity of airport characteristics to those airports in Rothfeld et al. (2019)'s case study;
- and/or applying Rothfeld et al. (2019)'s approach (originally intended for airports) to railway stations, in order to avoid the aforementioned bias favouring rail transport.

Additionally, results from such a study on railway station access and egress times as mentioned in the last proposal could be used to develop a more objective method for selecting railway stations belonging to cities. Optimisation models could combine rail travel times and station-specific access/egress times to find the station which provides fastest access to a city.

Aside from access and egress times, idle times at airports were simulated using a fixed time supplement of two hours as well, as per Durand and Romijn (2023). These idle times might differ in reality between airports, depending on factors such as their size (measured by, e.g., passenger volume), as well as the quality and quantity of check-in, luggage, security and customs facilities. Further research could investigate airport-specific idle times for air travel modelling. This may be carried out on the infrastructural side by using the aforementioned airport characteristics to estimate idle times, and/or on the user side by researching realised idle times of air travellers at airports or through surveys inquiring the idle times they would take into account for a specific airport.

6.3.3. Route formation

RQ2 has yielded the estimated night train demand for city pairs. Some of these city pairs' rail routes may lie in such geographical proximity, or have such an overlap, that they could be served by the same train. For illustration, disregarding on-board capacity constraints, the city pairs Amsterdam-Barcelona, Amsterdam-Madrid, Brussels-Barcelona and Brussels-Madrid could all be served by one Amsterdam-Madrid train, since its fastest route passes through Brussels and Barcelona anyway.

There are multiple ways to combine city pairs into a night train route. If there is an intention to serve both city pairs A-C and B-C (i.e., city A and city B each paired with city C) with one train, this could be achieved in any of the following ways:

- a route A-B-C;
- a route A-D-C, with travellers from B using a feeder service to join/leave the train at A or at an intermediate stop D;
- a route E-C, with travellers from both A and B using feeder services to join/leave the train at station E.

The range of these options for generating routes combining city pairs increases exponentially when more potential city pairs are included, especially when it comes to considering potential additional key stations D and E. Furthermore, whether it is necessary or even desired to combine city pairs will depend on the estimated demand and to what degree it would be able to fill the desired occupancy of the night train. For instance, if night train demand for city pair A-C alone already exceeds the desired minimum occupancy, there may be little point in seeking a route combining A-C with B-C, since there is no residual capacity for the additional passengers of B-C. That is, unless a second route would be created to house the residual passengers from A-C exceeding the maximum occupancy of the first route.

In exploratory research for this thesis, an attempt at a manual approach to route formation for city pairs to/from only the Netherlands has proven remarkably complex and difficult to optimise. Such a manual approach can hardly be up-scaled to the entire scope area. At a larger scale, the number of possible combinations of travel demand flows to form routes with sufficient occupancy to fill a night train may become extremely large, if not infinite. The same holds for model outcomes with many (small) flows, or if smaller flows than the exploratory minimum of 40 ED1D are to be taken into account as well. Further research may attempt to formulate a more structural and optimal method to form night train routes given demand estimations on city pairs. An basis for this could be the Transit Network Design and Frequency Setting Problem, as was already applied in a high-speed rail context by Grolle (2020).

6.3.4. Demand modelling

Due to time and resource constraints, the gravity model as applied in this thesis only determines changes in demand for a city pair based on travel time changes for that specific city pair independent of other routes. However, this approach ignores potential interaction effects between routes with changing travel times. Whereas the current modelling approach assumes travel demand always decreases if travel time increases, in the hypothetical scenario at hand of large-scale travel time increases across Europe, city pairs with a comparatively small travel time increase might find an increase in demand from destination-switching travellers who used to travel on connections that experience a comparatively large travel time increase from air to rail. Further research may develop an adapted version of the gravity model better suited to handle this type of travel behaviour.

Furthermore, the modelling approach as applied here only takes into account rail as a substitute for air travel. Interaction effects with other (road-based) modes have not been included. On the one hand, rail demand may currently have been overestimated if existing air demand would shift to car and bus (instead of train) when flights are removed. On the other hand, rail demand may have been underestimated if existing road demand would shift to rail when train services are newly introduced, accelerated or otherwise improved. Further research may both investigate the interaction between air, rail and road-based modes regarding demand shifts in case of maximum air travel substitution, and model the influence of the inclusion of road-based modes in the model on rail demand estimates.

6.3.5. Seasonality

The Eurostat dataset shows that existing air travel is not distributed uniformly across the year. Some connections have significantly lower or higher demand in different months or quarters of the year. Further research may explore the Eurostat data in more detail to analyse the prevalence of seasonality, and design an improved demand estimation methodology accordingly. For example, if demand is found to differ significantly between summer and winter months, the demand estimation process could be carried out twice on data constrained to each of those periods, in order to identify key destinations and demand patterns in summer and winter, respectively.

Furthermore, seasonality may affect idle times at airports as well. Airports experiencing high volumes of passengers, such as tourism-oriented airports might experience during the start, peak or end of summer or winter, may see slower throughput of their check-in, luggage, security and customs facilities if there are insufficient staff and/or facilities to handle the peak load. Further research may look into the (quantified) effect of peak passenger volumes on idle times at airports.

6.3.6. Effects on emissions

A main motivation for this thesis subject was the need for reduction of aviation's harmful greenhouse gas emissions. While this thesis has investigated a scenario in which flights within the scope area (a major part of Europe) were maximally substituted by rail travel, it has not been quantified what reduction in emissions the implementation of such a scenario would result in. As was already mentioned in Section 5.1.1, the removal of short- and medium-distance flights *ceteris paribus* may cause an increase in long-distance air travel, and thus an increase in total emissions as well (Dray, 2020). Further research may investigate the effect on total emissions of this maximum air-rail substitution scenario under different policy measures. These policy scenarios may include:

- policies prohibiting the use of substituted airport slots for additional (long-distance) flights;
- policies enforcing the closure of some airports and the concentration of remaining (intercontinental) flights on a smaller set of designated hub airports;
- or a low-policy scenario modelling the hypothesised increase in emissions through substitution of short- and medium-distance airport slots with long-distance flights, as mentioned above.

The resulting estimations of emissions may be used to evaluate the potential benefits of the implementation of the maximum air-rail substitution scenario researched in this thesis. They may additionally serve to assess different policy scenarios in order to determine which policy measures would be required to meet emission reduction targets.

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A

Appendix

A.1. Stations

Tables A.1, A.2 and A.3 show the manually kept dataset of train stations belonging to airport cities, and their coordinates, as described in Section 3.1.5.

- For Berlin, the main station's north-south low-level tracks (formerly known as ”Berlin Hbf (tief)”) have been used due to faster connections in and out of the city for almost all relevant directions compared to its west-east high-level tracks.
- For Billund, the geographically nearest station was Give.
- For Hahn, although the airport is called Frankfurt-Hahn, it is located more than 100 km away from Frankfurt (which also has another airport much closer to the city). Therefore, the most major city having Hahn as its closest airport was chosen, which was Koblenz.
- For Karlsruhe/Baden-Baden, Rastatt is a town and station in the middle between the cities of Karlsruhe and Baden-Baden.
- For Malmö, the main station's low-level through tracks have been used due to faster connections in and out of the city for all directions compared to its high-level dead-end tracks.
- For Mulhouse, also denoted as Basel-Mulhouse, the airport serves both the cities of Basel and Mulhouse. Basel's main station (Basel SBB) was selected due to the better connectivity as well as the local railway infrastructure allowing trains from both France and Germany/Switzerland to reach the station under that country's overhead power system (25kV AC and 15kV AC, respectively), as opposed to Mulhouse which is only accessible under the French overhead power system.
- For Paris, the city is served by multiple terminus stations each aimed at serving a different (high speed) line and direction, such as Gare du Nord for Belgium, Gare de l'Est for Germany and Gare de Lyon and Gare d'Austerlitz for Switzerland, Italy, Spain and the south of France. The station of Marne-la-Vallée-Chessy TGV, outside the city centre, has been selected since Railway Routing yielded the smallest deviation with the terminus stations for each of the relevant directions.

A.2. Rail travel time calibration

Table A.4 shows the list of city pairs used for calibration of rail travel times, with Railway Routing's calculated times and the retrieved timetabled times.

- For Munich-Ljubljana, with the fastest direct train (a night train) taking 7h37 as per timetable, two hours have been deducted to account for several long stops of this train (such as an 80-minute stop in Salzburg).

A.3. Demand estimation results

A CSV file of total air travel times, calibrated rail travel times, and daytime and night train demand estimation results for all city pairs can be found at https://tud365-my.sharepoint.com/:x:/g/personal/ddietzenbacher_tudelft_nl/EbE9KuiBDfFEkAgD-oGWTtYBvN_Qm4N7lJ2Ag5kk_MnjiQ?e=NTJDHN. *Please note that this file can, at the time of publication, only be accessed by Delft University of Technology accounts. Access beyond December 31st, 2024 is not guaranteed.*

A.4. Code

The code used to generate the results can be found at https://tud365-my.sharepoint.com/:u:/g/personal/ddietzenbacher_tudelft_nl/EQpEl2R6jv1MnwBIxUJ8_PIB5PnYEpZs45RAzTJAHLvW4g?e=rSKOMv. *Please note that this file can, at the time of publication, only be accessed by Delft University of Technology accounts. Access beyond December 31st, 2024 is not guaranteed.*

The code uses several data files: `data_airports.csv` (an edited version of Rafiee (2024)), `data_stations.csv` (the data in Appendix A.1), `data_flights.csv` (a dataset of flight times for all city pairs in the dataset) and `data_railtimes.csv` (a dataset of calibrated rail travel times for all city pairs in the dataset), which should all be in the same folder where the notebook is executed. This folder should additionally contain a subdirectory `Eurostat` which contains the Eurostat datasets used to retrieve flight passenger numbers.

City	Station name	Station latitude	Station longitude
Aalborg	Aalborg	57.042886	9.916760
Aarhus	Aarhus H	56.149787	10.202952
Alicante	Alacant Terminal	38.345939	-0.498935
Amsterdam	Amsterdam Centraal	52.378596	4.901565
Ancona	Ancona	43.607307	13.496415
Antwerp	Antwerpen-Centraal	51.215863	4.421101
Barcelona	Barcelona Sants	41.379276	2.140059
Bari	Bari Centrale	41.117440	16.869485
Beauvais	Beauvais	49.426133	2.088550
Bergamo	Bergamo	45.690439	9.675608
Bergen	Bergen	60.389485	5.335418
Bergerac	Bergerac	44.857280	0.489063
Berlin	Berlin Hbf (tief) *	52.525661	13.369042
Beziers	Béziers	43.336045	3.218785
Biarritz-Bayonne	Bayonne	43.497009	-1.470388
Billund	Give *	55.842953	9.236057
Bodo	Bodø-Baddadjø	67.286956	14.395169
Bologna	Bologna Centrale	44.506542	11.342397
Bordeaux	Bordeaux Saint-Jean	44.824762	-0.556130
Bratislava	Bratislava hlavná stanica	48.159140	17.106373
Bremen	Bremen Hbf	53.083209	8.813696
Brest	Brest	48.388452	-4.476585
Brindisi	Brindisi Centrale	40.634164	17.939102
Brussels	Bruxelles-Midi	50.835646	4.335850
Budapest	Budapest-Keleti	47.500355	19.085993
Bydgoszcz	Bydgoszcz Glówna	53.135402	17.991464
Caen	Caen	49.176790	-0.346879
Carcassonne	Carcassonne	43.218226	2.351487
Charleroi	Charleroi-Central	50.404456	4.438697
Clermont-Ferrand	Clermont-Ferrand	45.778924	3.101213
Cologne	Köln Hbf	50.942784	6.959071
Copenhagen	Koebenhavn H	55.672732	12.565109
Crotone	Crotone	39.084471	17.108395
Cuneo	Cuneo	44.388248	7.536305
Debrecen	Debrecen	47.519874	21.628636
Dortmund	Dortmund Hbf	51.517903	7.458923
Dresden	Dresden Hbf	51.039694	13.732529
Duesseldorf	Düsseldorf Hbf	51.219962	6.794357
Eindhoven	Eindhoven Centraal	51.443182	5.481437
Florence	Firenze Campo di Marte	43.777043	11.277326
Forli	Forli	44.224194	12.054749
Frankfurt	Frankfurt (Main) Hbf	50.106654	8.662581
Friedrichshafen	Friedrichshafen Stadt	47.653211	9.473755
Gdansk	Gdansk Glówny	54.356828	18.644464
Geneva	Genève-Cornavin	46.210532	6.141969
Genoa	Genova Piazza Principe	44.417640	8.920072
Gerona	Girona	41.979261	2.815874
Gothenborg	Göteborg C	57.709484	11.977222
Granada	Granada	37.184044	-3.610399
Graz	Graz Hbf	47.072610	15.416002

Table A.1: Table of cities (from A to G) with their stations and coordinates thereof.

City	Station name	Station latitude	Station longitude
Hahn	Koblenz Hbf *	50.350787	7.588302
Halmstad	Halmstad	56.669646	12.864872
Hamburg	Hamburg Hbf	53.553219	10.006582
Hannover	Hannover Hbf	52.376503	9.742362
Harstad/Narvik	Narvik	68.441714	17.442534
Helsingborg	Helsingborg C	56.043853	12.694683
Hyeres	Hyères	43.108792	6.124106
Innsbruck	Innsbruck Hbf	47.262885	11.400933
Kalkmar	Kalmar C	56.661156	16.361287
Karlsruhe/Baden-Baden	Rastatt *	48.861178	8.216497
Katowice	Katowice	50.257607	19.017146
Kaunas	Kaunas	54.885423	23.931098
Kiruna	Kiruna	67.867715	20.199994
Klagenfurt	Klagenfurt Hbf	46.615624	14.313716
Kosice	Kosice	48.722049	21.269145
Krakow	Kraków Glówny	50.068592	19.974991
Kristiansand	Kristiansand	58.145640	7.987168
La Rochelle	La Rochelle	46.152577	-1.145306
Lamezia	Lamezia Terme Centrale	38.921043	16.257249
Leipzig	Leipzig Hbf	51.345766	12.381785
Liege	Liège-Guillemins	50.624311	5.566721
Lille	Lille Europe	50.639211	3.075609
Linkoeping	Linköping C	58.417201	15.624340
Linz	Linz Hbf	48.290257	14.291706
Ljubljana	Ljubljana	46.058402	14.511373
Lodz	Lódz Kaliska	51.757574	19.430212
Lublin	Lublin Glówny	51.231303	22.568911
Lulea	Lulea C	65.582820	22.166194
Luxemburg	Luxembourg	49.599912	6.134738
Lyon	Lyon-Part-Dieu	45.760353	4.859868
Maastricht	Maastricht	50.849876	5.706035
Madrid	Madrid-Puerta de Atocha	40.404509	-3.688392
Malaga	Málaga María Zambrano	36.710704	-4.434721
Malmö	Malmö C *	55.609817	13.001268
Marseille	Marseille-St-Charles	43.304030	5.381702
Memmingen	Memmingen	47.985356	10.187028
Milano	Milano Centrale	45.487561	9.206076
Mo i Rana	Mo i Rana	66.309608	14.133500
Montpellier	Montpellier-St-Roch	43.604227	3.880336
Mosjoen	Mosjoen	65.844635	13.200161
Mulhouse	Basel SBB *	47.547049	7.588994
Munich	München Hbf	48.140690	11.556936
Munster	Münster (Westf) Hbf	51.956601	7.635412
Murcia	Murcia del Carmen	37.974405	-1.128320
Nantes	Nantes	47.217229	-1.540510
Naples	Napoli Centrale	40.852490	14.274926
Nice	Nice-Ville	43.704732	7.261384
Nimes	Nîmes	43.832429	4.366186
Nuernberg	Nürnberg Hbf	49.445623	11.082791
Oslo	Oslo S	59.910395	10.755739
Ostend	Oostende	51.227105	2.927556
Ostersund	Östersund C	63.170652	14.636813

Table A.2: Table of cities (from H to O) with their stations and coordinates thereof.

Paderborn	Paderborn Hbf	51.712860	8.740438
Paris	Marne-la-Vallée-Chessy TGV *	48.870204	2.782803
Parma	Parma	44.810195	10.329090
Pau	Pau	43.291342	-0.369694
Perpignan	Perpignan	42.696039	2.879416
Perugia	Perugia Ponte San Giovanni	43.091942	12.438299
Pescara	Pescara Centrale	42.468539	14.203971
Pisa	Pisa Centrale	43.708086	10.398431
Poznan	Poznan Glówny	52.401522	16.912090
Prague	Praha hlavni nadrazi	50.082794	14.436480
Pula	Pula	44.880368	13.847365
Reggio Calabria	Reggio Calabria Centrale	38.104583	15.636898
Rennes	Rennes	48.103072	-1.672389
Rijeka	Rijeka	45.330140	14.429469
Rimini	Rimini	44.064026	12.574872
Rome	Roma Termini	41.899582	12.504351
Ronchi De Legionari	45.830003	13.506231	
Ronneby	Ronneby	56.206340	15.283785
Rotterdam	Rotterdam Centraal	51.925194	4.469140
Rzeszow	Rzeszów Glówny	50.043047	22.005980
Saarbruecken	Saarbrücken Hbf	49.241401	6.990845
Salzburg	Salzburg Hbf	47.813062	13.045853
Sandefjord	Sandefjord	59.135338	10.222821
Sevilla	Sevilla-Santa Justa	37.392860	-5.973972
Skelleftea	Skelleftea	64.753925	20.951401
Split	Split	43.504352	16.443207
Stavanger	Stavanger	58.966586	5.731945
Stockholm	Stockholm C	59.329928	18.057382
Strasbourg	Strasbourg	48.585139	7.733941
Stuttgart	Stuttgart Hbf	48.785610	9.183396
Szczecin	Szczecin Glówny	53.418206	14.549224
Szczytno-Szymany	Olsztyn Glówny	53.785777	20.497656
Tarbes	Tarbes	43.240248	0.069340
Torino	Torino Porta Susa	45.071630	7.665276
Toulouse	Toulouse-Matabiau	43.611541	1.453907
Tours	Tours	47.388209	0.695357
Treviso	Treviso Centrale	45.659831	12.245228
Trondheim	Trondheim	63.436664	10.399632
Umea	Umea Central	63.830087	20.266992
Valencia	València Joaquín Sorolla	39.458396	-0.381544
Vaxjo	Växjö	56.876613	14.805091
Venice	Venezia Santa Lucia	45.442443	12.318855
Vienna	Wien Hbf	48.185302	16.377879
Villafranca	Verona Porta Nuova	45.428478	10.982181
Warsaw	Warszawa Centralna	52.228821	21.003160
Weeze	Weeze	51.624221	6.197979
Wroclaw	Wrocláw Glówny	51.098206	17.038035
Zadar	Zadar	44.105261	15.243251
Zagreb	Zagreb glavni kolodvor	45.804446	15.978833
Zaragoza	Zaragoza-Delicias	41.658622	-0.911318
Zurich	Zürich HB	47.378839	8.536893

Table A.3: Table of cities (from P to Z) with their stations and coordinates thereof.

From	To	Railway Routing (min)	Timetable (min)
Berlin	Frankfurt	186	236
Berlin	Cologne	198	237
Berlin	Munich	193	226
Frankfurt	Hamburg	180	212
Frankfurt	Duesseldorf	63	85
Frankfurt	Hannover	110	134
Duesseldorf	Munich	202	252
Munich	Vienna	197	243
Frankfurt	Basel/Mulhouse	123	165
Geneva	Zurich	129	161
Brussels	Amsterdam	83	112
Munich	Ljubljana	310	337 *
Luxemburg	Paris	96	131
Split	Zagreb	403	478
Paris	Basel/Mulhouse	131	184
Paris	Geneva	152	191
Milan	Rome	141	170
Rome	Naples	55	62
Rome	Florence	67	91
Munich	Budapest	312	411
Budapest	Vienna	120	158
Vienna	Kosice	264	350
Prague	Vienna	195	240
Prague	Kosice	364	465
Krakow	Warsaw	140	140
Hamburg	Copenhagen	225	277
Gothenborg	Stockholm	148	181
Malmö	Stockholm	204	265
Umea	Stockholm	255	372
Bergen	Oslo	310	398
Oslo	Trondheim	332	398
Oslo	Stockholm	307	308
Barcelona	Madrid	137	150
Madrid	Malaga	158	162
Madrid	Valencia	91	112
Madrid	Sevilla	125	153

Table A.4: Rail travel time calibration dataset, with city pairs and their rail travel times in minutes according to Railway Routing and the actual timetable (as retrieved at various moments during the spring of 2024).