

Passenger Welfare Effects of Relocating High-Speed Rail Stations from City Centres to Outskirts in the European Network

by

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Passenger welfare; High-speed rail; Relocation; Peripheral stations; Trans-European Network;
Combined mode-route choice model; Saturation analysis; SCBA

Preface

The master thesis that lies before you concludes my journey towards the degree of Master of Science in Transport, Infrastructure & Logistics. During the last seven months, I have immersed myself in the topic of high-speed rail. A mode that I believe has great potential in the energy transition, allowing us to continue visiting places and people in countries far away, but in a more sustainable way. The pursuit of this potential requires action from governments and companies, but also asks for innovative answers to complex questions. This is where I hope this thesis can contribute. It questions the conventionality of centrally located high-speed rail stations in European cities and provides novel recommendations that were substantiated through various quantitative methods.

My interest in high-speed rail was sparked in the fall of 2020. As I was starting my board year at the study association for Civil Engineering at the TU Delft, Het Gezelschap "Practische Studie", I got to know a master thesis student, and former board member, called Jorik Grolle. He invited us to attend his defence and I was intrigued. The presentation caught my attention since it was a combination of challenging, quantitative research and societal relevance, including a governance perspective. This combination was what I had sometimes missed in the primarily technical bachelor of Civil Engineering, inspiring me to consider enrolment in the master Transport, Infrastructure & Logistics.

As I am writing this, more than 3.5 years have passed since then and my thesis is approaching completion. The completion of this thesis, which combines various disciplines, would not have been possible without the guidance of my supervisory committee. Firstly, I want to thank Oded for his guidance and responsiveness throughout the project, and even more so for his enthusiastic and constructive way of providing feedback. Secondly, I want to thank Maarten, who especially assisted me in the decision-making process during the first months and provided me with much needed context in the later months. My gratitude also goes out to external supervisor Bernat, who provided me with applicable feedback from both his academic background and his work experience as policy analyst at the European Commission. Lastly, I want to express my thanks to Jorik, who inspired me prior to the start of this thesis and challenged me through his detailed and valuable feedback throughout the thesis.

In addition to thanking Jorik, I wish to extend my thanks to the company he represented as supervisor: Royal HaskoningDHV (RHDHV). The RHDHV colleagues helped me on several occasions and I am very thankful for their expertise. I especially want to thank Barth Donners. I have found the individual aspect of writing a thesis challenging, but the valuable feedback meetings with Barth frequently lifted my spirits. My thanks also go out to Wouter Leyds, a rail expert at RHDHV who helped me estimate essential values for the transport model. Lastly, I want to thank Lucas Spierenburg, PhD'er at the faculty of Civil Engineering, for assisting in the set-up of my passenger welfare experiments.

This thesis concludes not only my master programme but also seven years of studying and living in Delft. A formative period that I thoroughly enjoyed and that frequently challenged me. I want to express my sincere gratitude to the friends and family who were there for me along the way. Above all, I want to thank my parents. For supporting me in difficult times, like the first exam period in my bachelor of Civil Engineering programme, and backing me in the decisions that I made throughout these seven years. I dedicate this thesis to you.

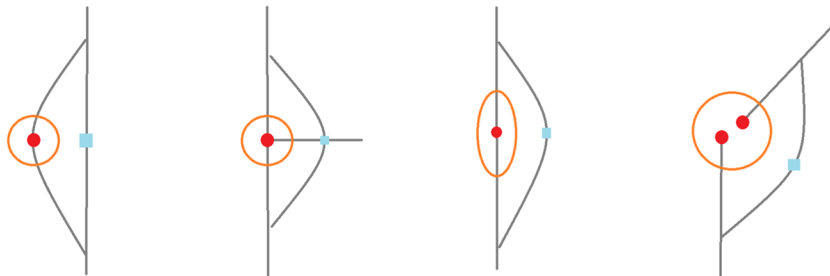
In conclusion, if you ever plan to travel from Amsterdam to Barcelona by high-speed train and wish to experience the passenger welfare benefits that are described in the thesis first-hand: I recommend that you take the peripheral TGV detour around Paris via Charles de Gaulle Airport and Marne-La-Vallée-Chessy. I wish you an interesting read!

*Bastiaan van der Hoeven
Delft, July 2024*

Abstract

While the romantic appeal of historic, centrally-located railway stations is undeniable, their efficiency in accommodating high-speed rail (HSR) services for passengers is questionable. The allocation of centrally-located stations benefits passengers who start or end their journeys in major cities, but imposes longer travel times for traversing passengers because trains generally reduce their speeds in urban environments. The majority of Europe's HSR-stations are located in these urban centers, where expansion options are severely restricted. Therefore, this study investigates the passenger welfare effects of relocating HSR-services from city centers to city outskirts, which could be an alternative to capacity expansion in existing stations. It does so by utilising a combined route-choice model, with the Trans-European Transport Network (TEN-T) policy for 2050 as input. This study forecasts the station bottlenecks for 2050 and examines various HSR-service relocation scenarios. A logsum-based economic appraisal method evaluates the impacts on passenger welfare of these relocations. The findings reveal substantial potential welfare benefits when HSR services are relocated to peripheral stations. The order of magnitude of these benefits to the European economy ranges from tens of millions of euros per year to a couple of hundred million euros per year. This range depends on the traversing passenger volumes and the comparative in-vehicle time savings and distance savings between peripheral and urban routes. Both of these savings originate from the most important predictor of passenger welfare effects: the network design. Examples of both advantageous and unfavourable network designs are provided in Figure 1. It is recommended to policymakers to not instantly dismiss the possibility of peripheral HSR stations from a protectionist point of view, but to consider the option for its relatively low construction costs and externalities, and especially the potential for substantial passenger welfare effects.

Advantageous rail network
designs for passenger welfare



Unfavourable rail network
designs for passenger welfare

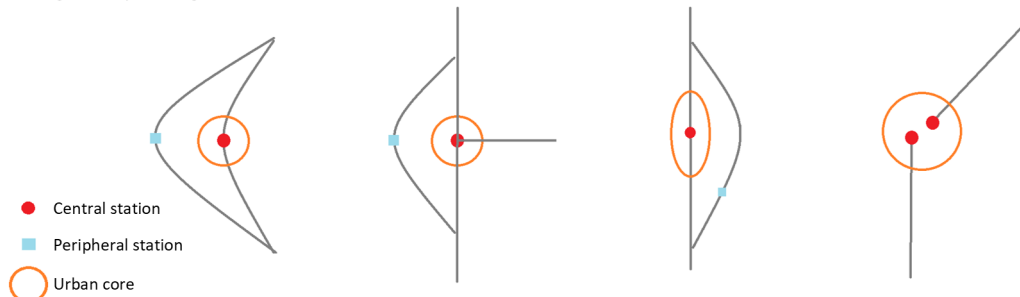


Figure 1: Identified network trends that impact the passenger welfare potential of peripheral HSR-stations.

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Introduction

1.1. Research context

The European Union has set a challenging goal: to become the first climate neutral continent in 2050. This target was recently defined in the Green Deal (European Commission, 2021b). Vital to obtaining this goal is that emissions from the transportation sector should have decreased with 90% compared to 1990. The other 10% in reaching net zero will have to be captured or removed directly from the atmosphere (European Commission, 2024). Obtaining an emission reduction of 90% will be complex, especially since both the passenger and freight transportation sector have only been increasing its green-house gas emissions since 1990 (Bigo et al., 2022). The increase in the passenger transportation sector can be attributed to a multitude of factors. The first is that the demand for passenger transport has increased with 31% since 1990. The increased emission level is however also caused by the modal shift of passenger transport that has taken place towards air transportation, growing in modal share from 6.5% to 10.1% in total passenger-kilometres between 1995 and 2016 (European Environment Agency, 2021). A troubling trend in the context of the EU decarbonisation targets.

The EU aims for railway transport to play an essential role in reaching the decarbonisation targets of the Green Deal (Keersmaecker and Wartberger, 2021). The reasoning is clear: trains produce relatively small amounts of CO₂ per kilometre (CE Delft, 2022) and it has been extensively proven that high-speed railways can compete with both European flights of up to 750 km distance (Adler, Pels, and Nash, 2010) as well as with road transportation (Yang, Chen, and Yang, 2022). The EU even states that intermodal competition is "fierce" (European Court of Auditors, 2018b). The potential is significant, especially since air and road transport currently account for more than 85% of CO₂ emissions in the global transport sector (Ritchie, 2020). One can conclude that an efficient (high-speed) railway network could contribute to achieving the EU environmental goals. However, the problem is that the current state of the European international railway network can barely compete with short-haul flights and international road travels. The European Court of Auditors has even called Europe's train network "an ineffective patchwork of national lines" (European Court of Auditors, 2018a).

The European train network might currently be a "patchwork", but the European Commission aims to integrate those patches through the Trans-European Transport Network (TEN-T) policy. The goal of this policy is to establish a unified European transport area based on an integrated Trans-European network that connects all member states (European Commission, 2021b). Multiple revisions have taken place since it was established in 1993. In 2021, TEN-T was revised to align with the EU Green Deal and the Sustainable and Smart Mobility Strategy (European Commission, 2021b). This revision placed a strong emphasis on the expansion of the European high-speed rail network and has set the goal of triple HSR passenger traffic per 2050, relative to 2015 (European Commission, 2021b). See Figure A.1 in Appendix A for the design of this network. Benefits of this network, in addition to contributing to decarbonisation targets, include the effects on social welfare (Adler, Pels, and Nash, 2010), economic development, social cohesion, and regional competition (European Court of Auditors, 2018a). Another reason for realising an HSR network is that it satisfies the increasing demand for travel. An example:

the demand for Interrail tickets has doubled since 2019 (Doyle, 2022).

The EU may have developed TEN-T, but the key to realising the different elements lies in the Member States (Proost et al., 2014). The EU encourages Member States by subsidising priority projects and providing political and financial support, but can and will not force them to cooperate (Bröcker, Korzhenevych, and Schürmann, 2010). This financial support extends to various infrastructure investments of the TEN-T, including the development of (high-speed) railways, such as the Malmö-Copenhagen bridge and railway stations (Kowalski, Marada, and Chmelík, 2023). However, the fragmented political environment across Europe, along with concerns about the profitability of HSR projects, poses significant challenges to a swift implementation of the TEN-T plans (Proost et al., 2014; European Court of Auditors, 2018a). In their cost-benefit analysis of 22 priority projects, Proost et al. (2014) used estimated passenger volumes for 2020, based on 2001 rail demand data, to estimate profitability. Their findings indicate that most TEN-T projects do not meet the cost-benefit criteria. This sentiment is echoed by the European Court of Auditors (2018a), who observed a general lack of cost-efficiency in their assessment of completed HSR lines. These conclusions contribute to the financial concerns of the Member States, who would be more inclined to construct the TEN-T infrastructure if they were deemed profitable. Substantiating a positive cost-benefit test is also made difficult by the fact that future TEN-T passenger volumes are not known in either practical or scientific literature.

Large infrastructural investments are necessary to accommodate the planned tripling of high-speed rail traffic per 2050. Extensive research on increasing the capacity of the edges in the Trans-European network has been conducted from both academic perspectives (Borgogno, 2023) and business perspectives (PTV Group, 2023), but the constraining capacity of the nodes is usually disregarded. The capacity of the European stations that provide, or will provide, HSR-services is an overlooked element in the literature. The follow-up question is how pressing this issue is. Some central stations like Stuttgart are relatively future-proof (Railtech, 2023) and others like Stockholm are already congested and have to plan for expansion (WSP, 2022). Moreover, the need for construction is not only caused by the increased number of trains in the future TEN-T network, but also because high-speed trains are increasing in length (European Commission, 2021b).

An alternative to expansion of station capacity is to redirect the railway route. An example of this is the HSR-relocation from Amsterdam Centraal (Luchtvaartnieuws, 2023) to Amsterdam Zuid (Banister and Givoni, 2013). Redirecting HSR-services is particularly interesting when the railway station in question is located in a historic building in a city centre, making capacity expansion relatively expensive and complicated. An additional, potentially stronger, argument concerns passenger welfare effects of relocating HSR-services from city centres to outskirts, which is the main focus of this research. A first indication that centrally-located stations might not be beneficial to passenger welfare is provided in Paris, where the peripheral detour is faster than the urban route (Fortuin, 2024).

The scientific relevance of this research is established through defining the knowledge gaps in section 1.3. Certain aspects do, however, also make this a societally relevant thesis. For example, this thesis provides arguments for a discussion on the desirability of city-outskirt HSR stations. The conclusions might even be of use in allocating funding for these types of HSR-focused stations, as the EU aims to fund this type of station in the essential railway junction of Brno (Kowalski, Marada, and Chmelík, 2023). Another aspect that makes this thesis societally relevant is the estimation of future passenger flows in the TEN-T in chapter 4. Having well-grounded passenger demand data for the separate railway elements available provides the opportunity to perform economic appraisal of different infrastructure elements. Both aspects provide knowledge in this field and, therefore, could contribute to developing HSR as a green alternative for long-distance travel.

As a last addition to this section on research context, it is worth highlighting the involvement of Royal HaskoningDHV in this thesis. Royal HaskoningDHV is an international engineering consultancy firm. Their core business is to provide clients with advice from their varying areas of expertise, like sustainable mobility and railway (station) development. Their clients are often governmental organisations that make the decisions on infrastructural investments as those discussed in this research. For this reason, Royal HaskoningDHV has supported the creation of this thesis.

1.2. Problem Definition

This section defines two problems concerning HSR-station allocation in the European context, as introduced in section 1.1. They are discussed in an order that reflects their assumed relevance.

Problem 1: Centrally-located HSR-stations are often ineffective for traversing passengers.

Section 1.1 provided an example that illustrates the statement of problem 1. This example describes that the peripheral detour around Paris is a faster option for traversing passengers than the urban route (Fortuin, 2024), although it should be noted that the case of Paris is a bit peculiar. Paris contains many terminus stations in the city centre, meaning that a city transfer between stations is a necessity when traversing through the city. This is a network configuration that also applies in Budapest and Paris (Matheisen et al., 2024). It would be more efficient for traversing passengers that pass these three cities if they did not need an inner-city transfer with a different mode.

This problem statement may be specifically true for these three cities, but it is assumed to also apply to many other cities. In many cases, it is expected that the in-vehicle time of the urban route is substantially longer than that of a hypothetical peripheral route. This statement comes from the fact that trains that travel through the outskirts of a city often maintain a higher average speed than those that travel through a city centre (Matheisen et al., 2024). The problem definition is especially true if the existing central station is a terminus station, which requires a train to travel the same railway twice in both directions.

In conclusion, the first and foremost problem of this section is that centrally-located HSR-stations are often ineffective for traversing passengers. These inefficiencies are expected to be worse for situations in which the central stations are terminus stations, and even more so when a transfer between stations is required. This first problem is especially relevant since many high-speed railway investments do not pass the societal cost-benefit test (Proost et al., 2014; European Court of Auditors, 2018b).

Problem 2: Capacity expansion options of centrally-located HSR-stations are costly and limited by spatial constraints.

Wenner and Thierstein (2022) have found that more than 60% of HSR-stations in Europe are located in existing city centers. These urban areas are usually very densely constructed with limited options for capacity expansion due to expensive ground and historic architecture, with the train station itself often also being a historic building. This might pose a substantial problem for the European Union's TEN-T ambitions of tripling passenger kilometres per 2050.

This second problem statement is especially true when expanding the capacity of existing centrally-located stations requires costly underground railway tunnels. European Court of Auditors (2018b) apply in their research a societal cost-benefit test on a set of urban rail tunnels in Europe. They concluded that none of them passed the test and that they often exceed the initially planned costs. An extreme example of exceeding costs is provided in Stuttgart, where the construction costs of the new railway tunnel ended up being 3.7 billion euros more expensive than initially agreed upon (European Court of Auditors, 2018b). As an alternative, it is sometimes advocated to construct a peripheral detour with lower costs (Moyano and Dobruszkes, 2017).

1.3. Knowledge Gaps

This thesis aims to fill two distinct knowledge gaps. The process of identifying these knowledge gaps through literature research can be found in chapter 2. The first one concerns the main knowledge gap, which is research focused, while the second is more of a practical nature. Filling the second one is a precondition to filling the main knowledge gap.

Knowledge gap 1: Quantitative research on the passenger welfare trade-off between central and peripheral HSR-stations is lacking

The main knowledge gap concerns the scientifically novel territory of examining the passenger welfare effects of HSR-service relocation from city centres to outskirts. The identification of this knowledge gap was inspired by HSR-services that are allocated in the outskirts of Chinese cities (Banister and Givoni,

2013; Zhen, Cao, and Tang, 2018; Loo and Huang, 2023). This is a phenomenon which is not seen much in the current European railway network, with the exception of the France TGV network. The French HSR-development policy explicitly aims to also create peripheral stations, while its neighbours like Italy, Spain, and Germany have decided to prioritise existing central stations (Albalade and Bel, 2016). An exception of a European peripheral station can be found in the UK, where a high-speed station is being developed on the city outskirts, close to the airport, which functions as a bypass to the centrally-located station in Birmingham (BBC, 2018).

In short, this knowledge gap was identified since research implies that passenger welfare benefits can be generated by relocating HSR-stations to the city outskirts (Banister and Givoni, 2013). However, no research to date is available that quantitatively assesses the extent to which passenger welfare benefits can occur when relocating high-speed rail services from centrally-located stations to city-outskirt stations, nor under which conditions they occur. In addition, research has been done on the strategic allocation of railways (Borgogno, 2023) and the allocation of stations within a city (Roy and Maji, 2022) to maximise passenger welfare, but no research has been done on the strategic allocation in the outskirts of a city. The few publications that concern city outskirt HSR stations discuss this from an urban development perspective, not from a passenger welfare perspective.

Passenger welfare, in this context, is understood as the monetary measure of consumer surplus, quantified through the LogSum as a representation of accessibility benefits (Ben-Akiva, 1985). This procedure is a direct valuation of how changes in HSR-station location affect passenger utility. Quantification of passenger welfare could also be used to optimise the locations of the HSR stations to maximise passenger welfare.

Knowledge gap 2: Traffic forecasts for rail passenger distribution on the future European railways, as envisioned in recent EU policies, are unavailable in literature

Secondly, there exists a practical knowledge gap regarding the future passenger volumes across the Trans-European rail network. The design of the TEN-T policy provides information on the planned future network (European Commission, 2021b), but no passenger distribution forecasts corresponding to the TEN-T policy have been made for a prediction year after 2030 (Donners, 2016). Hypothetical networks have, however, been modelled in academic and non-academic studies for 2050 (Borgogno, 2023; PTV Group, 2023).

The statement that filling this second knowledge gap is a prerequisite to filling the first one is true, since rail passenger volumes are required as input data to fill the first knowledge gap. Effectively, passenger flow volumes between European cities need to be effectively quantified to quantify passenger welfare effects when testing HSR-service relocations in the European context. In addition, relocation of HSR-services to a city-outskirt location can be a solution when centrally-located stations are at risk of being unable to satisfy future demand. It was described in the problem definition of section 1.2 how financial and spatial constraints complicate the option of expanding capacity at centrally-located stations, which is why relocation to the outskirts might be a fitting, alternative solution. To estimate which centrally-located stations in the Comprehensive TEN-T might become oversaturated, and which cities might therefore consider relocation to the outskirts, one would need the passenger distribution over the Trans-European rail network and therefore an answer to this knowledge gap. No literature was found specifically on the traffic and saturations of stations and urban nodes, but the TEN-T policy states that urban nodes often present bottlenecks and that the TEN-T does not contain plans to address this problem European Commission, 2021b

1.4. Hypothesis

Intuitively, moving HSR-stations away from the very accessible city centres feels as a downgrade. One could be inclined to think that it would only lead to a welfare loss. Especially since many popular travel guides mention the accessibility advantage of railway Central Stations over airports as one of the main advantages of long-distance rail travel over its competing modes (Lonely Planet, 2022). Furthermore, it is clear that local residents generally do not like the possibility of HSR services moving to a less central area (Hermelin and Gustafsson, 2022; Kowalski, Marada, and Chmelík, 2023), which is not surprising

since many people choose HSR over air due to its shorter access time.

Counter-intuitively, the hypothesis of this thesis is precisely that relocating HSR-services away from city centres could lead to substantial passenger welfare benefits. Especially in the Central European nodes of the 2050 Comprehensive TEN-T network where traversing passenger volumes are expected to be high, like in Munich. This hypothesis is based on the following consideration: The total negative welfare effects of increased access/egress time for origin/destination passengers are expected to be smaller than the total positive welfare effects of decreased in-vehicle time for traversing passengers. The assumption behind this is that there are many more people that travel past nodes with high centrality, thus Central European nodes, than that there are passengers that start or terminate their journey at these nodes. This is especially true for Central European towns with relatively low local generation and attraction. An essential element to this hypothesis is that trains that travel through the outskirts of a station could maintain a higher average speed than those that travel through a city centre, which is illustrated by sources like Matheisen et al. (2024).

A scenario in which passenger welfare benefits are expected to be amplified is when two HSR-stations that are located in the same city are replaced by one HSR-station in the city outskirts. Two examples of cities with multiple HSR-stations are Paris, accommodating Gare du Nord, Gare du Est and Gare du Lyon, and London, with King's Cross St. Pancras International for most directions and Euston Station specifically for South-East England.

In addition, Manuel Weiß and Münster (2022) state that stations located on the outskirts of a city benefit more from travel time gains from a substantial expansion of the HSR network than stations located centrally. In other words, the peripheral stations have a higher relative increase in accessibility when the network expands in size. This makes sense since the city outskirts stations, which might initially be less accessible compared to central city stations, gain more in terms of reduction of travel time and connectivity when new routes or links are added to the HSR network. In conclusion, one could say that the building of a city-border HSR-station becomes an increasingly better option as the TEN-T network expands.

1.5. Research Objective

This thesis aims to fill the two previously defined knowledge gaps and to verify the hypothesis in the context of Europe in 2050. The execution of this process is presented in the upcoming chapters, according to the research questions of section 1.6. This objective was realised as described in the following paragraph, which summarises the process of this thesis.

Firstly, the European long-distance passenger distribution was forecast with a transport model that predicts volumes for 2050, filling the previously defined knowledge gap 2. The second step was to quantify passenger volumes at HSR-stations in city centres, calculate the corresponding saturation levels, and identify bottlenecks. Lastly, passenger welfare effects of both existing and hypothetical peripheral stations were calculated using various experiment sets. The cities that contain the defined bottlenecks were included in the experiment sets for the hypothetical relocations. When assessing the hypothetical relocations, two types of relocations were considered. The first option was relocation to an airport in the city outskirts. The second type of experiment was a strategic relocation that aims to maximise welfare gain (or possibly; minimise loss) within a certain vicinity of that city. Finally, the results were analysed in the context of two different research sub-questions. The experiments and their interpretation provided for filling the main knowledge gap and for testing the hypothesis.

1.6. Research Questions

The following research question is defined to achieve the objective from section 1.5:

To what extent, and under which conditions, can the relocation of high-speed rail services from centrally-located stations to city-outskirt stations lead to passenger welfare gains?

The main concept of this question, which involves the relocation of high-speed rail (HSR) services from centrally-located stations to city-outskirt stations, corresponds to the main knowledge gap in section 1.3

and to the hypothesis in section 1.4, and does not need further elaboration. However, there are some elements that need clarification. Firstly, the main research question does not necessarily concern a full HSR-station relocation, but rather the relocation of HSR-services from a central to a peripheral station. This decision was made because it might be more valuable to add a peripheral HSR-station to the network, instead of completely replacing a centrally-located station with a peripheral one. Secondly, "to what extent" refers to the quantification of the passenger welfare effects in monetary units. Third, "under which conditions" refers to network conditions such as the network layout and the composition of passenger traffic.

This research divides the main research question into six sub-questions that make the thesis both more comprehensible and more structured. These are the following:

- Q1 Which centrally-located HSR-stations in the 2050 TEN-T network can be identified as potential bottlenecks based on forecast passenger volumes?
- Q2 What is the potential of existing HSR-stations, which provide a detour in the city outskirts by 2050, to generate passenger welfare benefits?
- Q3 What would be the passenger welfare effects of relocating HSR-services to an airport on the outskirts of a city, relative to maintaining them at stations with high centrality?
- Q4 What would be the passenger welfare effects of relocating HSR-services to a strategic city outskirts location that maximises passenger welfare, relative to maintaining them at a location with high centrality?
- Q5 Which conditions contribute to passenger welfare benefits of peripheral HSR-stations?
- Q6 What is the relative size of the assessed passenger welfare effects in social cost-benefit analyses that appraise the construction of high-speed railway stations?

The expected 'oversaturation' of station capacity, as referred to in Q1, is considered an argument for HSR-service relocation, as discussed in section 1.3. Especially since many (traversing) passengers are expected to use these stations with capacity problems, thus providing a high potential for welfare effects of peripheral relocation. It provides a motive for this research question and a scope. The selection of 2050 as prediction year is further discussed in section 1.7.

The concept of relocating HSR-services, as referred to in Q3 and Q4, is visualised in Figure 1.1. Both sub-questions include the crucial assumption that commuter trains remain at the centrally-located stations, since it is detrimental to daily commuters if their origin or destination station is moved to the city outskirts (Kowalski, Marada, and Chmelík, 2023). The approach to answering each sub-question is discussed in chapter 3 and they are eventually answered in chapter 7. From now on, this thesis will refer to the sub-questions by using Q1, Q2, Q3, et cetera.

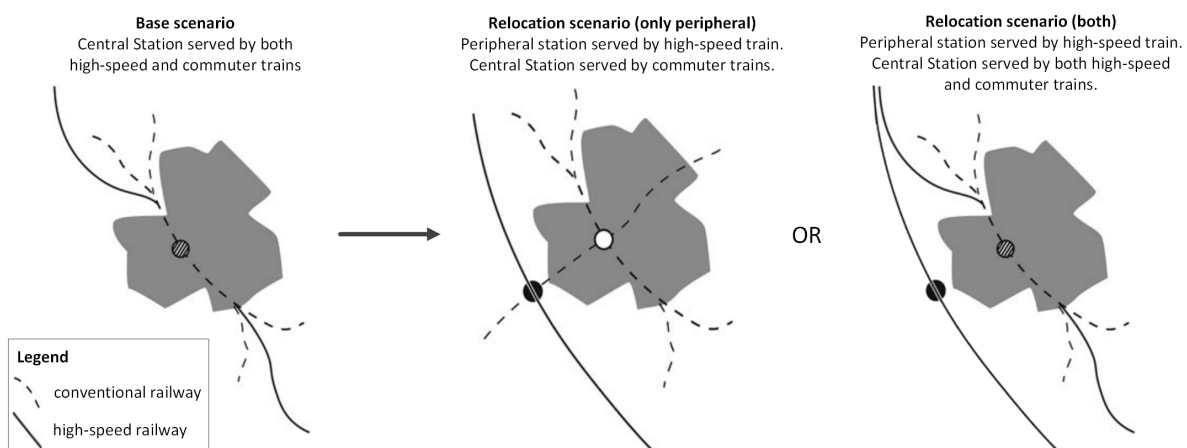


Figure 1.1: The concept of relocating all or a share of the HSR-services from a central station to a peripheral station. Adapted from Wenner and Thierstein (2022).

The possibility of relocation of HSR-services to an airport is included in the sub-questions, specifically Q3, for a multitude of reasons. In general, building HSR-stations at airports provides the potential for economic, mobility, and climate benefits (Malott, 2022). In addition, the inclusion of this experiment aligns with the goal of the EU to ‘connect all core network airports to the rail network, preferably high-speed’, as stated in the EU White Paper by the European Commission (2011). Another argument is that infrastructure for access and egress to the airport location already exists, which makes the relocation of the HSR-services relatively cost-efficient. An example of the mentioned mobility benefits is that the relocation of the HSR-station would simultaneously improve the accessibility of the airport. The last argument is that such a multimodal hub also contributes to the development of HSR as a complementary mode, a development which is advised in literature (Malott, 2022; Borgogno, 2023). However, this development does not play a role in this research, since multimodal trips are excluded from the transport model in chapter 4.

Lastly, Q6 is included to provide context for the potential implications of the effects of passenger welfare generated in the economic evaluation. Many high-speed rail investments have previously been discussed to do not pass the societal cost-benefit tests (Proost et al., 2014; European Court of Auditors, 2018b). Therefore, passenger welfare benefits have the potential to be decisive in contributing to the passing of cost-benefit tests. Q6 puts the generated passenger welfare effects of Q2, Q3, and Q4 into context and asks whether they would be substantial in the economic justification of HSR-investments.

1.7. Scope

This section defines various boundaries for this research and determines what is included and what is not. It contains the policy scope, the scope of time, the geographical scope, the modes considered for long-distance travel, and an overview of key definitions. The list of key definitions is included since it sets some essential quantitative and qualitative boundaries that are essential for the execution and comprehension of this research. More specific assumptions are presented at the end of each chapter where they apply.

1.7.1. Scope of Policy

The TEN-T policy has been referred to many times in this introduction, but it is essential to define the revision that is applied for modeling the future European railway network, since revisions are published in relatively rapid succession.

The TEN-T policy regulation that is used as input for this research is the one from European Commission (2021b). It is the most comprehensive regulation out of the set of recent ones, containing many detailed transport maps for both Member States and Neighbouring Countries. A more recent amendment, composed as a result of the Russian war of aggression in Ukraine, does not include maps of neighbouring countries and was therefore not applicable for this research.

A multitude of arguments were taken into consideration while selecting one specific policy as the base scenario for the transport model:

- The use of the TEN-T regulation provides realism. Passenger welfare experiments could also have been executed with a transport model in a hypothetical long-distance context, but the use of an actual transport policy document has multiple advantages. Real-world cases improve interpretability of the research compared to hypothetical cases. Additionally, the results of real-world cases are potentially interesting for various types of readers. These results and byproducts can be relevant for local to European policymakers, scientists and students alike, private parties in the rail sector, and consultancies like the Royal HaskoningDHV (assisting company in this research).
- The use of the TEN-T 2021 policy has the advantage that much has been written about it, including an impact assessment by the European Commission itself and reports by external parties. The actual routes can also be traced. This offers opportunities for both input and validation of the transport model.
- The use of the TEN-T 2021 policy contains a clear geographical context and timeline with milestones. This provides a framework for the scope of time and geographical scope.

- The use of a comprehensive policy on a European scale means that no national policy documents need to be collected and analysed. The plans of the TEN-T 2021 policy are assumed as a starting point and national policy plans are not included unless specifically defined otherwise.

The latter argument, stating that the TEN-T policy is the main policy that is applied in this thesis is true but for three local exceptions. All three are implemented in the approach of this research since they have previously been discussed in this introduction or are discussed in the literature study, and are related to the concept of this thesis. The first one being the relocation of HSR-service from Amsterdam Centraal to the more sub-urban Amsterdam Zuid (Banister and Givoni, 2013). This is not a relocation to the city outskirts but it is less central. The second policy plan that is included is the replacement of the current Birmingham station by the central Birmingham Curzon Street and the peripheral Birmingham Interchange, which is a fine example of relocating HSR-services partially to the city outskirts (BBC, 2018). The third one is the relocation of the centrally located Brno station to a new sub-urban station (Municipality of Brno, 2023).

1.7.2. Scope of Time

The reason to research the European 2050 network (Comprehensive TEN-T Network) is that new HSR infrastructure, including HSR stations, should be constructed in a future-proof manner with a long-term perspective (Hermelin and Gustafsson, 2022). Since it takes 16 years to construct new HSR infrastructure and the average life-cycle of infrastructure objects is 60-80 years, one would ideally perform this research for 2100. However, TEN-T policy plans do not exist post-2050, so that is why this thesis is scoped for 2050. An example of this is Q1, which identifies which existing stations are expected to be bottlenecks in 2050. If HSR-services are relocated due to a bottleneck in 2050, the new HSR-station should however always be designed with a capacity in mind that fits the stated lifespan of 60-80 years (Rasker et al., 2023). This capacity could be estimated through extrapolating the 2050 demand results from this research with the use of natural growth percentages for the passenger transport sector.

In addition to the year of prediction, 2050, the base year is defined as 2024. Defining the base and prediction year is necessary for executing one of the methodological steps of this research, which is quantifying the Net Present Value of the aforementioned passenger welfare effects. 2024 is selected as base year since it is the publication year of this thesis.

1.7.3. Scope of Geography

The areas included in this research are those that are located on the mainland of the European continent plus the one island that is connected by rail, being Great Britain. This geographical scope (largely) corresponds with the countries that are discussed as Member State or as "neighbouring country" in the 2021 TEN-T policy regulation (European Commission, 2021b).

The exclusion of Ireland is the one and only difference between the geographical scope of this research, being Continental Europe and Great Britain, and the TEN-T policy. The reason for exclusion of this island state is that it is not connected by a railway bridge with the considered geographical area. This isolation means that the long-distance passenger flows between Ireland and the included areas would not directly impact the rail passenger distribution in the 2050 TEN-T network.

Two other EU island states, Cyprus and Malta, are also excluded for not having a rail connection with the mainland. This exclusion corresponds with the railway section of the TEN-T policy regulation, in which they are also excluded (European Commission, 2021b).

An overview of the geographical scope can be found in Figure 1.2. The 27 Member States of the EU are abbreviated as EU27 in the legend and in the continuation of this report. A "neighbouring country" is a state which is not an EU member, but is included in this research because it impacts the railway passenger distribution over the TEN-T railway network.

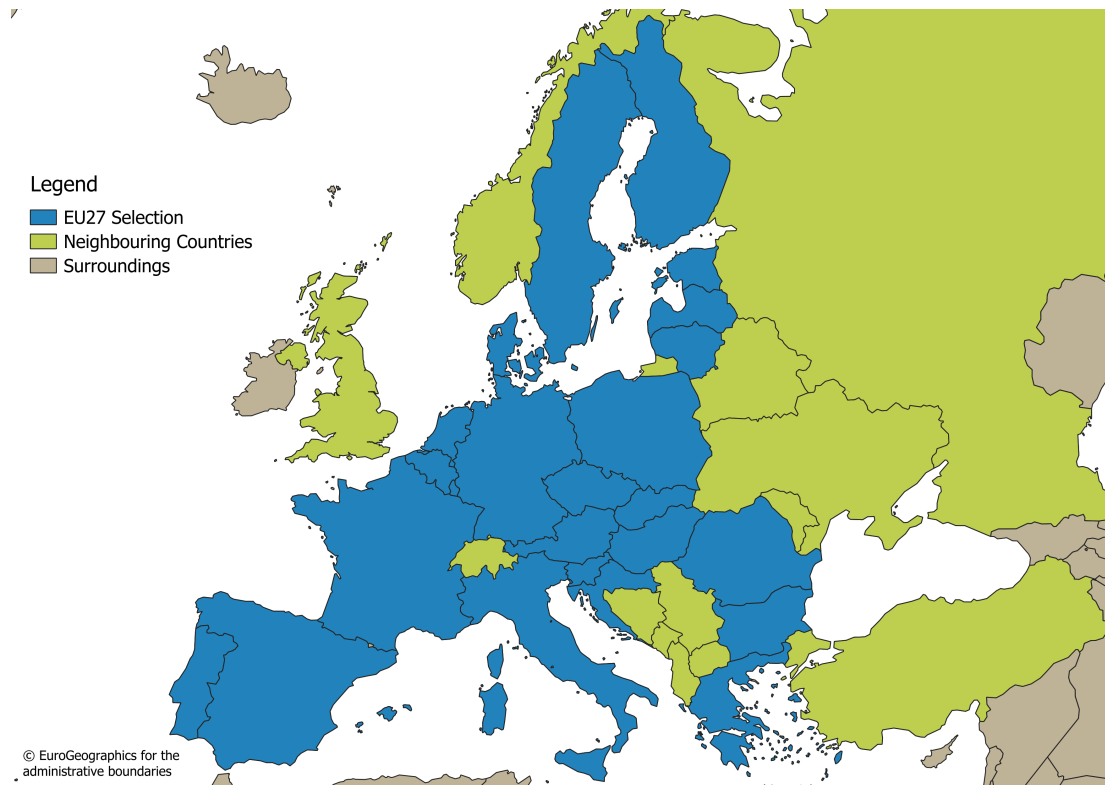


Figure 1.2: The geographical scope. Adapted from Eurostat (2020a) data and created with QGIS (2023).

1.7.4. Scope of Modal Choice

A preliminary step to quantifying passenger volumes over a railway network is modelling the modal choice that long-distance passengers make. chapter 3 describes what this methodological step entails, but which modes are taken into account for long-distance modal competition is defined here.

Section 1.1 discussed how inter-modal competition between air, road and rail is "fierce" (European Court of Auditors, 2018b). Previous transport models have taken into account various sets of modes when assessing the long-distance passenger distribution. Most of them include the aeroplane, car and train as vehicles (Borgogno, 2023; Tanner, 2023; Grolle et al., 2024) and exclude the bus as a long-distance mode. This is because of the research by Donners (2016), who included the bus as a long-distance mode. One of his main results is that the bus is only competitive up to distances of 200 km due to its very non-competitive travel times. This conclusion is also the reason for excluding the bus as a potential mode in this research.

This research assumes that long-distance passengers use only one type vehicle for their journey, excluding access and egress modes, and assesses train, car and plane as the three distinct modes. It does however not separate conventional rail and high-speed rail as two different modes like Donners (2016) and Borgogno (2023). Appendix A shows that most destinations in Europe would be unreachable by only taking either the conventional train or high speed train, which would be the consequence of differentiating the two types of rail and not allowing inter-modal travel in a transport model. The TEN-T policy itself also views the railway network as an integrated international network, comprising high-speed rail and conventional rail. This is why this research assesses the inter-modal competition between three distinct modes on three different networks; car on road, planes in the air and (both types of) trains on railways. The different railway speeds are however not neglected, they are incorporated in the travel times per travel route as displayed in Appendix A and discussed in chapter 3.

1.7.5. Key Definitions

This last subsection presents a set of definitions that occur frequently throughout the document. The reason for inclusion in the scope section is that quite a number of the definitions scope the research through the provided definitions. An example of this is the definition of the term 'Peripheral area', which is essential to this research, of which the definition contains a numeric constraint. The definitions are provided alphabetically in Table 1.1 and Table 1.2.

Table 1.1: Key definitions table (1/2).

Term	Definition
Central area	Areas within a city where the population density per km ² is higher than 1500. This definition aligns with the "Urban Centre" definition proposed by multiple international organisations, including the EU United Nations Statistical Commission (2020).
City outskirts	The peripheral area that surrounds a city within a Functional Urban Area. The definitions of "Peripheral area" and "Functional Urban Area" are found below.
Conventional train	Conventional trains are regular trains that operate with speeds below 200 km/h, according to European Commission (2021b). Analysis by Donners (2016) showed that in 2015 their speed was on average 110 km/h. The European Commission (2021b) aims to implement a new standard speed for passenger rail of 160 km/h per 31 December 2040 to create a more coherent network that complements the HSR. This research assumes, based on this and the fact that the entire geographical scope is EU, that the average conventional train speed is 140 km/h per 2050.
Functional Urban Area	A Functional Urban Area contains both a city as well its commuting zone. The concept of the FUA is developed by the EU and Organisation for Economic Cooperation and Development and encompasses the economic and functional extent of cities based on daily passenger flows OECD (2023). This research assumes these areas as the catchment areas of urban nodes in the long-distance passenger network. See section 4.1 for more information.
Geodistance	Refers to the measurement of distance between two points on the Earth's surface. This distance is often calculated by taking into account the spherical shape of the Earth, using geographical coordinates (latitude and longitude) of the two points. Methods such as the Haversine formula are used to calculate this distance in kilometres.
High-speed train	A high-speed train is a train that operates at on average more than 200km/h according to European Commission (2021b). This research assumes, based on the speed regression analysis of 30 European HSR lines by Donners (2016), that the average operating speed of HSR is 220 km/h per 2050.
Long-distance travel	Long-distance travel is defined as a trip that extends the distance of 200 kilometers. This is consistent with the scope of Grolle et al. (2024), which is practical since this research uses elements of his transport model as input.
Induced demand	Induced demand refers to newly generated demand as a result of increased supply of infrastructure , like roads or rail. Essentially, as you make it easier to travel by adding capacity, more people choose to travel or travel more often.

Table 1.2: Key definitions table (2/2).

Term	Definition
Peripheral area	Areas located on the outskirts of the urban node. This research defines peripheral areas as rural areas in the proximity of a city, specifically within the Functional Urban Area of an urban node (Dijkstra, Poelman, and Veneri, 2019). The United Nations Statistical Commission (2020) labels an area as rural when it has a density of at most 300 inhabitants per km ² . If a squared kilometre has a population density less than 300 but is completely surrounded by urban or central areas, it is considered an urban area.
TEN-T	The Trans-European Transport Network (TEN-T) regulation refers to the policy document of the European Commission (2021b). Of the recent revisions of Trans-European Transport Network (TEN-T), this version is the most comprehensive and applicable report. See the first paragraph of this scope section for more details.
Terminus Station	A terminus station is where a railway line ends, serving as the final destination for trains that arrive there. Trains either end their journey or reverse out of the station to continue in the opposite direction.
Through Station	A through station is a station where trains are able to pass in the same direction without terminating. At these stations, trains arrive from one direction, unload and load passengers, and are then able to continue in the same direction.
Urban area	Areas within a city where the population density per km ² is lower than 1500 but higher than 300. This definition aligns with the "Urban Cluster" definition proposed by multiple international organizations United Nations Statistical Commission, 2020.

1.8. Readers Guide

This introduction has set the research landscape, defining the problems, knowledge gaps, the objective, research questions, and scope. Chapter 2 contains a literature review that examines studies on long-distance travel modal competition and station allocation strategies. The methodology used in this thesis is presented in chapter 3, detailing analytical frameworks and models to forecast passenger distributions, identify bottleneck stations, and assess implications for passenger welfare. Chapter 4 presents predictions for passenger distributions over the TEN-T by 2050 and chapter 5 examines the saturation of HSR stations that are located in city centres. The investigation of the effects on passenger welfare of the peripheral HSR-station experiments in chapter 6 provides a means to answer the main research question. Chapter 7 answers the research questions in the conclusions section and includes both discussions and recommendations. Appendices are referred to whenever they belong to the contents of the main text and often concern results.

In addition to the results available in the appendices, even more data can be found on the 4TU international data repository (4TU Federation, 2024). Data and models underlying this thesis will be available on that platform around the time of publication. Datasets can be found by prompting the title of the publication in the search bar.

2

Literature Review

The goal of this literature review is twofold. The first focus is to provide the reader with understanding of the competition for long-distance passenger transport between rail, air and road transport and the methods to model estimate the corresponding modal split and passenger distribution. Secondly, it provides the reader with a literature analysis on the allocation of train stations with HSR-services and the corresponding welfare effects of such allocation decisions. The lay-out of this chapter mostly separates these two distinct focuses throughout its content, with the exception for the final synthesis. An ancillary aim of this chapter was to acquire data sources from literature for use in the succeeding chapters. This aim was defined since this research field is infamous for reliable, openly-accessible data (Donners, 2016).

This literature review consists of multiple sections. The methodology used to find the relevant literature is presented in section 2.1, both for the focus on long-distance travel competition and for the focus on HSR-stations. The literature that was found by using these methods is then analysed in section 2.2. This section discusses what theories and methods are used in literature, but also what defines these papers opposed to comparable literature. This analysis has again been divided in two subsections for the two distinct literature study elements. In the synthesis, section 2.3, overarching conclusions from both literature analyses are combined, two research gaps are defined and an overview of applicable data sources is provided.

2.1. Search procedure

2.1.1. Scope

The conceptual framework in Table 2.1 provides the keywords considered and used for retrieving relevant literature on competition between HSR and air transport on the long distance. These search terms are used to narrow down the scope of this paper. It was decided that 'High-speed rail' and 'Air transport' are the keywords that should be mentioned in every search command. A keyword for road transportation is excluded, since it was assumed that more research had been done on the competition between the relatively sustainable train and the highly polluting aircraft. The keyword 'Competition' was added to find papers that research the competition between not only air and rail transport, but also with other modes. 'Mode choice model' was added with the aim of finding applicable choice behaviour models. The alternatives for the keyword 'Mode choice model' were selected, as presented in Table 2.1, since Logit models are common mode choice models that estimate mode choice through quantification of the utility per alternative. The provided combination of keywords as shown in the truncation row generated the first set of literature.

Table 2.2 has the same set-up as Table 2.1, but focuses on finding literature on HSR-station location decision-making. 'High-speed rail' and 'stations' are in every command. Since the goal was to find and synthesise literature on location decision-making of train stations, the key word 'location' was also included in two out of three search prompts. A method to quantitatively aid such a decision-making process could be a welfare impact analysis, i.e. a quantitative analysis of the public benefit per allocation

alternative, which is why this was also included in two out of three search prompts.

Table 2.1: Conceptual framework for literature review on modelling long-distance travel.

Concept groups	High-speed rail, Air transport, Competition, Mode choice model	
Keywords	High-speed rail	HSR, High-speed rail, High-speed train
	Air transport	Airlines, Air transportation, Air travel
	Competition	Market competition, Airlines railway competition
	Mode choice model	Mode choice, Choice modelling, Logit, Utility
Truncation	(High-speed rail) AND (Air transport) AND (Competition) OR	
	(High-speed rail) AND (Air transport) AND (Mode choice model) OR	
	(High-speed rail) AND (Air transport) AND (Competition) AND (Mode choice model)	

Table 2.2: Conceptual framework for literature review on HSR-station allocation.

Concept groups	High-speed rail, Stations, Location, Welfare	
Keywords	High-speed rail	HSR, High-speed rail, High-speed train
	Stations	HSR-stations, Train stations, Hubs
	Location	Allocation, Relocation
	Welfare	Passenger welfare, Welfare effects, Public benefit, Economic appraisal
Truncation	(High-speed rail) AND Stations) AND (Location) OR	
	(High-speed rail) AND (Stations) AND (Welfare) OR	
	(High-speed rail) AND (Station) AND (Location) AND (Welfare)	

2.1.2. Selection criteria

Two criteria were used to select the papers relevant to the research topic of this research and of good quality. These are the following:

1. The paper has to be a published article in a journal. The reason for this criterion is that articles in a journal are peer-reviewed and have to be accepted by the journal, which should ensure the quality of the research.
2. Papers that are more than ten years old should either have a high citation rate (+50) or be cited in a significant number of the other papers on the literature list, indicating that they are landmark papers within the field of research.

There are a few exceptions on these criteria. Three master theses that have not been published in a journal are included in Table 2.4. The reason for including these reports is that they fit the defined scope of this study very well, originate from a recent year and some of their research data is available online. One other exception is (Malott, 2022), which is a conference paper. However it is also included in an edition of the Springer Book Series on 'Socioeconomic Impacts of High-Speed Rail Systems', which implies that the authors of this book deemed it of sufficient quality. The last exception is the work by Banister and Givoni (2013), since it fulfils the first criterion, is close to fulfilling the second criterion and is very applicable to the defined conceptual framework.

2.1.3. Strategy

The search techniques used to generate the final literature list are described in this subsection. Scopus is the search engine that has been used the most for this literature study (Elsevier, 2024), however Google Scholar has also been consulted occasionally (Google, 2024). The first relevant papers were discovered using the search criteria in Table 2.1 and Table 2.2. Setting the "Sort by" option in Scopus to "Cited by" was an additional procedure for locating the papers that were expected to be most relevant. Following the initial prompt results, a core of five articles with numerous citations were selected for both frameworks. From there, a forward-backward snowballing strategy was used to locate other fitting papers. The concluding literature list is shown in section 2.2.

2.2. Analysis

2.2.1. Long-distance travel competition

About 20 years ago, Milan Janić was one of the first to research the competition between High-Speed Rail (HSR) and Air Transport (AT). He wrote that HSR can compete with AT over a relatively large range of distances, namely 400 to about 2000 km (Janić, 1993). These findings were based on a costs minimisation competition model in which he used an estimated Value of Time to calculate the passenger costs and the total costs. His conclusion on the distances at which they compete were based on some numerical experiments with the model. This paper is the oldest out of the entire literature list provided in Table 2.3 and Table 2.4, but it was included since it is a landmark paper in this research field. It has been cited by multiple, more recent papers from the literature list (Adler, Pels, and Nash, 2010; D'Alfonso, Jiang, and Bracaglia, 2016; Wan et al., 2016; Grolle et al., 2024). Important to note is that Janić may have been one of the first to research HSR-AT competition, but the publication is also unique in its appliance of a costs minimisation method. Since then, almost all papers discussing this competition have used utility maximisation to quantify market shares. One can clearly see this in the "Method" column of Table 2.3 and Table 2.4.

Following up on this first paper, the second and third oldest papers are case studies, conducted in Australia (Hensher, 1997) and Spain (Román, Espino, and Martín, 2007). In the first one, an HSR corridor was proposed but not yet materialised. At the time, the corridor was dominated by air transport for business passengers and road transport for non-business passengers. To quantify potential market demand, a stated choice (SC) experiment was designed and conducted. The results were modelled in a heteroscedastic extreme value choice model, which is a generalized logit model where the variance of the error terms differs across the alternatives. Two main conclusions were that constructing the railway would generate induced demand, as a consequence of the improved corridor accessibility, and that the predicted revenues could form a financial risk (Hensher, 1997). Román, Espino, and Martín analysed the competition between HSR and AT using a mix of Revealed Preference (RP) and SC experiments. Their conclusion was that even under favourable conditions for the HSR, its market share would not exceed 35% on the Madrid-Barcelona corridor. In general, the authors cast doubt on the competition HSR can exert in the transport market due to low rate of returns (Román, Espino, and Martín, 2007).

A fourth, more recent, case study aims to add additional variables, safety and duty-free shopping, to the classical mixed logit model to better reflect the choices made between air and railway transportation (Lee, Yoo, and Song, 2016). Its conclusion was that the goodness of fit improves with these new choice variables and, just like (Hensher, 1997), that the characteristics of business and non-business passengers are different. Another, even more recent case study, does not compare AT and HSR, but studies the competition between a potential Hyperloop service and AT on an American corridor (Voltes-Dorta and Becker, 2018). The authors also apply discrete choice modeling, but in this case in the form of a multinomial logit (MNL) model. One can conclude from the last two paragraphs that logit models, albeit of various forms, have become common in the modelling of long-distance travel.

In chapter 1, HSR was described as an environmentally friendly transport mode when compared with long-distance travel via road and air. Although it is correct that the emitted CO₂ per distance is lower, the HSR network in China shows that constructing HSR does not necessarily lead to lower greenhouse gas (GHG) emissions (Chen et al., 2016). This can be explained by the 'significant' effect of induced demand after HSR-investments, which was previously mentioned in the context of (Hensher, 1997). The accessibility between Chinese regions has increased significantly since the start of China's ambitious national HSR strategy in the early 2000s. This increased accessibility has positively impacted the economy and social welfare, especially in eastern China where the Chinese cities with the highest centrality are located (Jiao, Wang, and Jin, 2017). However, the increased accessibility has also led to an increase of GHG emissions from the Chinese transport sector, since more individuals have started travelling long distances. Another paper that discusses the environmental impacts of HSR, and includes the effects of induced demand, focuses on the case of the London-Paris market (D'Alfonso, Jiang, and Bracaglia, 2016). It models the effects of AT-HSR competition on the environment and concludes that the introduction of HSR generally reduces the level of GHG emissions from the transport sector. D'Alfonso, Jiang, and Bracaglia (2016) however describe, after reviewing empirical data from

Givoni and Dobruszkes (2013), that induced traffic forms about 6 to 37% of HSR ridership after entry. This is a significant amount of people who would not have travelled that distance if the HSR was not introduced. A main take-away from these papers is that the effect of induced demand is significant in the context of HSR-investments.

China's HSR network has generated a lot of scientific attention since it became the largest in the

Table 2.3: Literature list part 1: Long-distance travel competition (1993 to 2016)

Title	Author	Year	Keywords	Method	Journal
A model of competition between high speed rail and air transport	Milan, J.	1993	Air transport; High-speed rail; Network; Competition; Passenger costs; System costs	Network modelling, Costs minimisation	Transportation Planning and Technology
A practical approach to identifying the market potential for high speed rail: A case study in the Sydney-Canberra Corridor	Hensher, D.A.	1997	Heteroscedastic extreme value switching model; High-speed rail demand; High-speed rail market potential	SC Experiments; Utility Modelling	Transportation Research Part A: Policy & Practice
Competition of high-speed train with air transport: The case of Madrid-Barcelona	Román, C.; Espino, R.; Martín, J.	2007	Competition; Service quality; Stated preference; Willingness to pay	SC experiments; RP experiments; Utility Modelling; Willingness to pay	Journal of Air Transport Management
Assessing spatial equity and efficiency impacts of transport infrastructure projects	Bröcker, J; Schürmann, A.; Korzhenevych, A.	2009	Trans-European networks; Infrastructure policy; Spatial computable equilibrium	Spatial computable general equilibrium (SCGE) model	Transportation Research Part B: Methodological
High-speed rail and air transport competition: Game engineering as tool for cost-benefit analysis	Adler, N.; Pels, E.; Nash, C.	2010	Airlines; High-speed rail; Network optimisation; Applied game theory; Infrastructure pricing	Network optimisation; Applied game theory; Utility modelling	Transportation Research Part B: Methodological
Do the selected Trans European transport investments pass the cost benefit test?	Proost, S.; Dunkerley, F.; Van der Loo, S.; Adler, N.; Bröcker, J.; Korzhenevych, A.	2014	Cost benefit analysis; Europe; Transport infrastructure	CBA; Computable general equilibrium (CGE) modelling	Transportation
Competition of spatial service hinterlands between high-speed rail and air transport in China: Present and future trends	Wang, J.; Jiao, J.; Du, C.; Hu, H.	2015	High-speed rail; Civil aviation; Spatial analysis; Service market; China	Accessibility analysis	Journal of Geographical Sciences
The impact of high-speed rail investment on economic and environmental change in China: A dynamic CGE analysis	Chen, Z.; Xue, J.; Rose, A.Z.; Haynes, K.E.	2016	High-speed rail; Land use; Economic impact; Environmental impact; CGE modeling; China	Computable general equilibrium (CGE) modelling	Transportation Research Part A: Policy & Practice
A study on travelers' transport mode choice behavior using the mixed logit model: A case study of the Seoul-Jeju route	Lee, J.; Yoo, K.; Song, K.	2016	SC experiments; Mixed logit model; LCC; HSR; Undersea tunnel	SC experiments; Utility modelling	Journal of Air Transport Management
Air transport and high-speed rail competition: Environmental implications and mitigation strategies	D'Alfonso, T.; Jiang, C.; Bracaglia, V.	2016	High-speed rail; Airlines; Competition; Environment; Mitigation policies; London-Paris market	Utility modelling; Competition modelling	Transportation Research Part A: Policy & Practice
Airlines' reaction to high-speed rail entries: Empirical study of the Northeast Asian market	Wan, Y.; Ha, H.; Yoshida, Y.; Zhang, A.	2016	Difference-in-difference estimator; High-speed rail; Airline available seats; Northeast Asia; Propensity score matching	Utility modelling; Econometric (CGE) modelling; Propensity scoring; D-in-D estimation	Transportation Research Part A: Policy & Practice

world. The quick development and the fact that its total track length is unprecedented makes it a perfect area of study for transportation researchers. The case of the Chinese HSR network is the prime example of AT-HSR competition. Wan et al. (2016) researched the impact of the HSR entry on the Northeast Asian airline market. They concluded that for short-haul distances, i.e. less than 500km, HSR dominates the airlines. Furthermore, they also deduced the more surprising conclusion that the Chinese HSR negatively impacted the demand for both medium-haul and long-haul flights, depending

on the speed of the HSR. Important to note is that the effect of HSR on the long-haul flight market was not found in Japan and South-Korea, suggesting that this finding is not universally true. Another article finds the same conclusions for the impact of HSR on China's demand for AT, but also finds that the impact of HSR on AT is very dependent on the travel fares of both modes (Zhang, Yang, and Wang, 2017). After entry of the HSR, the air travel demand is simply much more elastic. Zhang, Yang, and Wang (2017) also find that the travel time and travel cost have much stronger effect on the mode choice than the service frequency. The described findings from the Chinese HSR network, as presented in this paragraph, are applicable in both the set-up and validation of a long-distance transport model.

The trends that were found in China have not only been identified for ex-post analysis, they have also been used to make predictions for the future (Wang et al., 2015). As HSR-networks expand, Wang et al. (2015) predict that the overlapping market for HSR and air transport will become increasingly large. This increase in competition is fueled by the fact that they both tend to serve areas with high population densities and well-developed economies.

Table 2.4: Literature list part 1: Long-distance travel competition (1993 to 2023)

Title	Author	Year	Keywords	Method	Journal
Erasing Borders, European Rail Passenger Potential	Donners, B.J.H.F.	2016	Potential; 4-step model Effective capacity; Long-distance; Barriers; EU-policy	4-step model; Gravity model; Random Regret Minimisation	<i>N/A: Unpublished MSc thesis</i>
Impact of high-speed rail on China's Big Three airlines	Zhang, Q.; Yang, H.; Wang, Q.	2017	High-speed rail; Chinese airline industry; Travel; time; Frequency; Fare difference	Econometric price elasticity modelling	Transportation Research Part A: Policy & Practice
Impacts of high-speed rail lines on the city network in China	Jiao, J.; Wang, J.; Fengjun, J	2017	City network; Centrality; High-speed rail; Train frequency; Network analysis	Network analysis; Central flow theory	Journal of Transport Geography
The potential short-term impact of a Hyperloop service between San Francisco and Los Angeles on airport competition in California	Voltes-Dorta, A.; Becker, E.	2018	Hyperloop; Airport competition; Catchment area	Utility modelling	Transport Policy
Factors Affecting Travel Mode Choice between High-Speed Railway and Road Passenger Transport —Evidence from China	Wen, Y.; Quanliang, C.; Jing, Y.	2022	High-speed rail; Logit model; Passenger's modal choice; Road passenger transport	SC Experiments; Utility modelling	Sustainability (Switzerland)
The Connectivity of the Long-distance Rail and Air Transport Networks in Europe	Bruno, F.	2022	Connectivity; Long-distance travel; Air to rail modal shift; Substitutability; Competitiveness	Network modelling; Network structure analysis	<i>N/A: Unpublished MSc thesis</i>
Roadmap Towards a Unified European High-speed rail Infrastructure	Borgogno, F.	2023	High-speed rail; Long- distance travel; European Rail; Network growth model	Iterative network growth model; Parametric infrastructure design	<i>N/A: Unpublished MSc thesis</i>
Service design and frequency setting for the European high-speed rail network	Grolle, J.; Donners, B.J.H.F.; Annema, J.A.; Duinkerken, M.; Cats. O.	2023	Network Design; Long- distance travel; Line Configurations; High-speed rail	Transit Network Design and Frequency Setting Problem; Network Optimisation; Utility modelling	Research Part A: Policy & Practice

At the other side of the globe, in Europe, the railway network is much less developed. The European Union (EU) therefore aims to improve the network through the Trans-European Transport Network (TEN-T) policy (European Commission, 2021b), which has been previously discussed in chapter 1. One of the key problems, however, is that some of these infrastructure projects are not only financially feasible from a business perspective but also from a societal perspective. An example of this is provided by Proost et al. (2014), who claim that many projects that are part of the TEN-T Core Network, the priority list, fail the social cost-benefit test and would need extra European subsidies or investments to ensure their viability. An additional, complicating factor is that the EU consists of a large group of Member States, and not all of them benefit equally from TEN-T subsidies. A similar paper quantifies, with a similar socio-economic evaluation, that 12 out of 22 projects have a yearly rate of return which is more than 5% (Bröcker, Korzhenevych, and Schürmann, 2010). The others were deemed unprofitable.

HSR projects are often defended on the basis of social welfare and environmental grounds (Proost et al., 2014), but the previous pair of papers have shown that this is no guarantee for a positive social cost-benefit ratio. The results of Adler, Pels, and Nash (2010) do, however, imply that some of the TEN-T projects could be justified, despite their vast fixed costs. The authors use game engineering and optimisation as tools for a social cost-benefit analysis, with utility modelling again being one of the methods used. The main difference with other analyses, which have seen less positive results, derives from the fact that Adler, Pels, and Nash (2010) use a network model. The authors claim that other analyses have undertaken a too distinct approach of evaluating individual projects, without incorporating aggregate network effects, while their network model allows for incorporating these, often positive, aggregate effects. Adler, Pels, and Nash (2010) generally conclude that the EU should encourage the development of HSR across Europe if they are interested in maximising social welfare. The paper also contains a valuable result concerning the competition between long-distance modes. The authors conclude from their model that the real competition between HSR and air takes place up until a distance of 750 kilometres and that the rail system attracts less passengers in long-haul markets.

One can deduce a few valuable conclusions from these three papers in the European context. Firstly, it is often a close call whether HSR projects add value to the economy. Additionally, it can be concluded that a commonly used method for economic appraisal in such projects is (social) cost benefit analysis (SCBA), which allows for including both financial and non-financial effects. This is a necessity, since HSR projects are often defended on the basis of welfare and environmental benefits. Lastly, Adler, Pels, and Nash (2010) suggest that it is necessary to apply a comprehensive network model to accurately estimate the beneficial welfare effects of an HSR investment.

Since almost all published papers have been discussed, the focus of this subsection shifts to four recent publications on the literature list in Table 2.4, including the three theses that were selected separately to the selection criteria in subsection 2.1.2. The commonality between these four publications is that they originate from the TU Delft, where research on HSR-developments has been increasing over the last decade. Elements of these analyses will recur in considerations in chapter 3 and chapter 4 of this thesis. They are discussed in chronological order of publication year.

The first one worth discussing is "Erasing Borders, European Rail Passenger Potential" by (Donners, 2016). Donners applied a 4-step transport model on the European passenger transport system, allowing him to quantify the rail passenger potential for various scenarios for continental Europe per 2030. The conclusions entail a potential increase of the international share of rail trips with 37% per 2030 in the maximum growth scenario, illustrating that there is much potential for long-distance rail travel. The mode choice model he opted for was a Random Regret Minimization (RRM), which is a divergence from the previously discussed studies that used logit models. Donners' reasons for selecting RRM include that it takes into account the performance of other alternatives in the selection of an alternative, and that it has a better fit on the market share in the calibration of his model. These arguments were taken into account in the selection process of the mode choice model for the transport model of this research in subsection 3.2.3. Another noteworthy aspect is the comprehensiveness of his OD-set, containing 125 urban nodes. More recent studies, like Tanner (2023), have not exceeded Donners' level of detail. On other matters his approach was relatively straightforward, adopting only time as a choice attribute and generating the travel distances by applying an average detour factor per mode on measured geodistances. Lastly, Donners defines an unconventional mode choice set. This set contained not only the three main modes for long-distance travel, i.e. train, car and plane, but also the bus. The results illustrate that the bus is only competitive up to 200 kilometres, which is why it was excluded in the definition of the mode choice set in section 1.7.

Under the supervision of Donners, a thesis was published in 2020 called "A Unified Design of the European High-Speed Rail Network," which was published in a journal a few years later and is cited in this thesis as Grolle et al. (2024). Given the publication date of the corresponding thesis, it is treated as the second source from this selection of four sources from the TU Delft. This paper applies the "Transit Network Design and Frequency Setting Problem" (TNDFSP) to optimise the European High-Speed Rail (HSR) network, showing that better design and centralised governance can significantly enhance

service efficiency and sustainability. In the process of applying that method, a long-distance passenger demand estimation is performed based on airport traffic data from 2019 in combination with estimated market shares of Donners (2016). This approach is further elaborated on in subsection 4.4.1. Furthermore, this thesis is similar to Donners (2016) in some aspects, like the application of RRM and the urban node selection, but different in estimating travel attributes and the applied methodologies. The way in which data from Grolle et al. (2024) was applicable to this research is discussed in section 4.2.

The thesis by Bruno, 2022, provides a comprehensive analysis of rail and air transport in Europe and introduces a connectivity index to compare their effectiveness and appeal. It reveals that while air travel efficiently connects major cities, the rail network shows significant performance disparities across regions. The study concludes that the rail network faces challenges in longer distances and is less integrated than air travel. To improve the HSR-network and reduce environmental impacts, enhancing rail services for journeys under 500 km and improving inter-modal connections is suggested. Bruno concludes that even though rail is currently more complementary to air, rail could potentially compete on longer routes with appropriate developments. An noteworthy result is that, currently, one needs at maximum two transfers to travel per plane between every node pair in the EU, while this number is seven per train. These number of transfers and the distribution of it were quantified using air and rail services from 2022 as input to the model. The applicability of these results is discussed in more detail in section 4.2.

The last thesis to discuss is the one by Borgogno (2023), who developed an iterative model for network growth in the EU, focusing on where and when to build HSR infrastructure within existing budgets under centralised decision-making. His findings underscore the advantages of centralised planning and evaluation, stressing the need for a collaborative approach and enhanced European institutional investment management with increased financial authority. Just like in Donners, 2016, a RRM is applied to model passenger mode choice. The conclusions of Borgogno (2023) suggest where to strategically build high-speed rail infrastructure between urban nodes, but not where to strategically build stations along these strategically generated edges. The benefits that are included in the appraisal, that determines the strategic location, are travel time savings and externality savings. Borgogno explicitly assumes that the stations are located centrally in the urban nodes.

2.2.2. HSR-station allocation

When researching the topic of allocation of train stations that provide HSR services two things stand out immediately. The first is that most of the research has been published quite recently and that they are often case studies, a trend which is also identified by Manuel Weiß and Münter, 2022. The second is that many papers that discuss the impacts of HSR stations focus on urban development. Examples of this are Banister and Givoni (2013), Wenner and Thierstein (2022), Manuel Weiß and Münter (2022) and Loo and Huang (2023), which can be found in Table 2.5. The inclusion of these four papers with a focus on urban development might seem strange in the context of this research, but they do provide very useful context on HSR-stations stations.

In their study, Banister and Givoni (2013) provide an in-depth analysis of the trends of High-Speed Rail (HSR) in Europe, with particular emphasis on the development of HSR stations and their funding mechanisms. They identify two critical factors pivotal to HSR line planning: the number and location of stations within the network, and the integration of these stations with the broader transportation network. When discussing the allocation alternatives for stations with HSR-services they present two: a 'city-centre' and a 'city-outskirt' location. In the case of the 'city-outskirt' option they advise to integrate the HSR-station with existing airports to maximise accessibility, which is in-line with the paper of Malott, 2022. Banister and Givoni also state that many European cities should not have more than one HSR-station due to the levels of demand for travel.

Many authors, including Banister and Givoni (2013), Zhen, Cao, and Tang (2018), Yang et al. (2019) and Loo and Huang (2023), identify that HSR stations in Asian countries like China and Taiwan are often detached from the city center and located in the periphery. While in Europe they are mostly located within the 'natural' boundaries of a city, with most of the exceptions being in France. Loo and Huang (2023) make this conclusion after analysing 1627 HSR-stations across Chinese and European cities

from an urban science perspective. The authors expect this to be related to the fact that China has experienced rapid urbanisation over the last decades, while many stations in Europe are historic and have seen the city develop around it.

Allocating an HSR-dedicated station to a city-border leads to poorer accessibility of the HSR-services and sometimes a disconnect between conventional train services and high-speed services, but it can also lead to lower travel times for traversing passengers. This shows that there are both positive and negative effects of allocating an HSR-station on the city-border. These benefits and losses can be split up in two categories, namely direct transport effects and non-transport effects. Direct transport effects refer to a result of improved or decreased accessibility, while non-transport effects refer for example to environmental effects and the impact on local economies. The previously identified papers that focus on urban developments mainly focus on the non-transport effects.

Banister and Givoni (2013) do however also discuss direct transport effects, providing a simple economic model to assess whether there is a case for constructing a new station. They state that there is a case for the construction of a new station if the reduction in access cost is larger than the construction costs of the station plus the time loss of those rail passengers only passing through the station. Banister and Givoni mention an example of the use of this model to quantify the welfare gain of moving the HSR services from Amsterdam Centraal to Amsterdam Zuid. Using this model in the context of relocating HSR-services from a 'city centre' to a 'city-outskirt' location, a new station at the city-border could be deemed welfare enhancing if the increased access and egress cost is smaller than the travel time gain of passengers that only pass through the station, taking into account the construction costs of expanding the city centre option or constructing the city-border option. One of the principle take-aways of this paper, but also of Wenner and Thierstein, 2022, is that new HSR-station locations, should always be well-embedded in public transport networks and this should play a large role in the decision-making process.

Manuel Weiß and Münter (2022) mainly focus on the spatial impacts of urban development in HSR-station areas. They do however also make a couple of valuable remarks that were of worth to this research. The first is that the authors identify a knowledge gap for quantitative studies on socio-economic effects of HSR-station allocation in Germany, with only a socio-economic study, two regional economic studies and the study of Wenner and Thierstein (2022) being available on this topic. A second noteworthiness is that stations that are located in the outskirts of a city benefit more from travel time gains of a substantial HSR-network expansion or improvement, than stations that are located centrally. In other words, the peripheral stations have a higher relative increase in accessibility when a network expands or improves. This makes sense since peripheral or city-border stations, which might initially be less accessible compared to central city stations, gain more in terms of travel time reduction and connectivity when new routes or links are added to the HSR network. To put this finding in the context of this research; peripheral HSR-stations become an increasingly better option as the TEN-T network develops.

The publication by Wenner and Thierstein (2022) is the last paper from Table 2.5 that focuses on HSR-stations in an urban development context. The authors analyse land use change for many European cases, in correlation with the evolution of station placement strategies. The urban development context may not have been very applicable to this research, but Wenner and Thierstein do provide in this paper a very useful analysis of the different connection types of station locations across Europe, defining seven classes of regions with HSR access and quantifying their presence across Europe. From these seven types, the "Metropolitan Multi-Hub", "Existing Urban Hub" and "New Node" can be identified as conventional, centrally-located station locations, accounting for more than 60% of all HSR stations. While "Peripheral Replacement" and "Regional Halt" can be classified as regions with dedicated city-outskirt HSR-stations. The visual concept of "Peripheral Replacement" has previously been provided in Figure 1.1 in section 1.6. "Distributed Services" refer to urban nodes where the high-speed services are distributed over both a central station and a peripheral station. "Bypass/Branch" simply means that many high-speed services cross an urban region, but only a few make a stop at the central station, while most bypass the city without stopping. The development of these regions with HSR-access and their connection types can be seen in Figure 2.1. It can be concluded that more than 60% of the regions

Table 2.5: Literature list part 3: Allocation of HSR-stations

Title	Author	Year	Keywords	Method	Journal
Access mode choice for relocated airports: the new Athens International Airport	Psaraki, V.; Abacoumkin, C.	2002	Airport relocation; Ground access; Modal split	Survey; Segmentation; Classification; Discrete choice modelling	Journal of Air Transport Management
High-Speed Rail in the EU27: Trends, Time, Accessibility and Principles	Banister, D.; Givoni, M.	2013	High-Speed Rail; TEN-T; Funding; Growth; Travel Time; Accessibility	Literature Review; Trends Analysis	Built Environment
Attracting travellers to the high-speed train: a methodology for comparing potential demand between stations	Marti-Henneberg, J.	2015	High-speed railway; Intermodality; Medium-size cities; Station	Graphical Information; System (GIS) Gravitational model	Journal of Transport Geography
Mind the services! High-speed rail cities bypassed by high-speed trains	Moyano, A.; Dobruszkes, F.	2017	High-speed rail; Bypass; Service supply; Servicing intermediate cities	Literature review; Classification; Spatial Analysis	Case Studies on Transport Policy
The role of access and egress in passenger overall satisfaction with high speed rail	Zhen, F.; Cao, X.; Tang, J.	2018	High speed train; User satisfaction; Rail transit; Quality of service; Well-being	Path analysis; Parsimonious Model; Literature review	Transportation
Mode choice in access and egress stages of high-speed railway travelers in China	Yang, H.; Dijst, M.; Feng, J.; Ettema, D.	2019	Access/egress stages; high-speed railway (HSR); China; mode choice	Land use model; Descriptive analysis; Discrete Choice Modeling	Journal of Transport and Land Use
Strategic Planning for High-speed Rail Investments – A Comparative Study of Four Intermediate Stations in Sweden	Hermelin, B.; Gustafsson, S.	2021	High speed rail; sustainable development; strategic planning; multi-level governance; Sweden	Literature review; Empirical study; Case study	Planning Practice & Research
High speed rail as urban generator? An analysis of land use change around European stations	Wenner, F.; Thierstein, A.	2021	High-speed rail; railway stations; urban development; transit-oriented development	Literature review; Data analysis; Classification	European Planning Studies
The impact of city public transportation use on the competitiveness between high-speed rail and the car: The example of the Prague – Brno connection	Kowalski M.; Marada M.; Chmelík J.	2022	high-speed rail; accessibility model in GIS; modal competition; Prague; Brno; Czechia	Accessibility analysis; GIS	Review of Economic Perspectives
High-Speed Rail as a driver of urban development? A contrasting comparison of station areas in Germany	Weiße, M.; Münter, A.	2022	High-Speed Rail; urban development; governance; transit-oriented development	Case study; GIS; Spatial impact analysis	EJSD
The Benefits of Building High Speed Rail Stations at Airports	Malott, P.	2023	High speed rail; Intercity rail at airports; Growth planning	Literature review; Case study	<i>Conference paper</i>
Location matters: High-speed railway (HSR) stations in city evolution	Loo, B.P.Y.; Huang, Z.	2023	High-speed rail; Natural cities; Zipf's law; Rank-size rule; City evolution; Station location	GIS; Natural City Model; Regression analysis; Statistical Analysis	Cities
High-Speed Rail Station Location Optimization Using Customized Utility Functions	Roy, S.; Maji, A.	2023	Central business districts; Costs; High speed rail; Location; Optimization; Railroad stations	Location optimisation; Utility maximisation; GIS	IEEE Intelligent Transportation Systems Magazine

in Europe that are connected by HSR are connected through use of a centrally-located station.

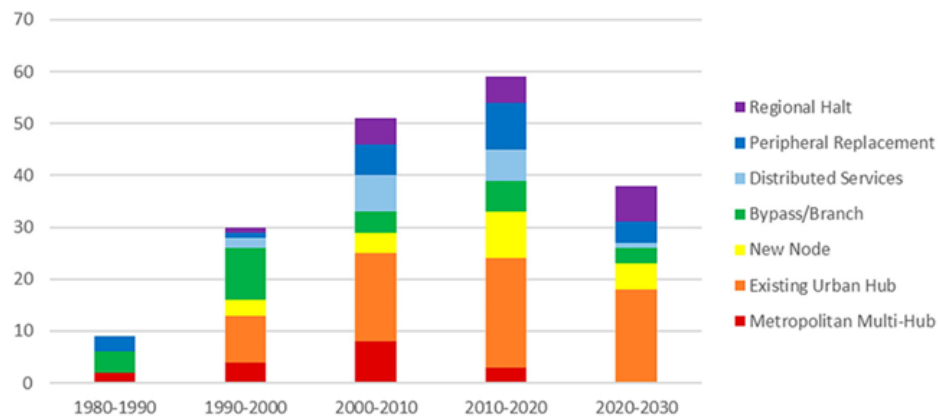


Figure 2.1: Occurrence of HSR-connection types across urban regions in Europe per decade (Wenner and Thierstein, 2022).

Similar to Wenner and Thierstein (2022), Marti-Henneberg (2015) contains a classification of HSR-stations based on location. This classification analysis is utilised in the context of quantifying potential demand between two HSR-stations. The classifications used are "Central", "Peripheral" and "External". The difference between the last two being that "Peripheral" has at least some connection with conventional railways and that "External" is completely disconnected except for the HSR services. The paper shows graphically how in Europe most stations are "Central" while in Asia most are "External". Besides this, Marti-Henneberg advocates that intermodality should be encouraged around HSR-stations, especially if located in non-metropolitan areas. Marti-Henneberg also identifies a problem in the governance of HSR stations, stating that: "An HSR station is a point at which all levels of management should converge; from the EU to the municipal level." In his views, the lack of this management has led to many ineffectively located HSR-stations in Europe.

Previously, Banister and Givoni (2013), Borgogno (2023) and Marti-Henneberg (2015) have recommended to integrate HSR-stations with airports to create multi-modal hubs with the aim of improving their combined accessibility. A case study that delves into these potential benefits is provided by Malott, 2022, who assesses these benefits in the context of travel in the Cascadia region in the USA and Canada. Malott examines why high speed rail stations should be built at major airports, such as SeaTac Airport in Seattle, and concludes that fast trains at airports are beneficial for the transport operators themselves, local economies and climate goals. The reason for Malott's argument for the case of Cascadia is twofold. The first is that demand is not satisfied by the, approximately, 1-hour flights between urban nodes like Portland, Seattle and Vancouver due to the constraints at the airports, implying that there is unmet demand for long-distance travel options. The relatively small distances also mean that HSR can compete with the airplanes very well, as was discussed in subsection 2.2.1. The second is that Canada aims to further reduce their carbon emissions, since they are not on track to meet the Paris Climate Accord goals. Malott concludes his paper with the recommendation of HSR as a "game-changing investment in fast, high-capacity, clean-energy transportation" and expects that the realisation of HSR-infrastructure would push down emissions. Malott's argumentations, along with those from Banister and Givoni (2013) and Borgogno (2023), were reason to consider the potential of relocating HSR-services to airports in this research.

An additional paper on the subject of airports elaborates on the decision-making process of an airport relocation, focusing on access mode choice in the context of discrete choice modelling Psaraki and Abacoumkin (2002). In summary, Psaraki and Abacoumkin (2002) estimate ex-ante through a logit model how the access/egress modal split will develop due to the relocation of the Athens International Airport from an urban area to a more peripheral area, and compare this with initial situation. The elaboration on access mode choice and the corresponding initial modal split data was directly applicable for this research, as will be seen in section 4.2. In addition, Psaraki and Abacoumkin, 2002 emphasise that an efficient access system is a prerequisite for peripheral airports that aim to maintain

the attractiveness of more centrally-located airports. It is assumed that this efficient access system requirement also applies for relocating HSR-services to a "city outskirts" location.

Several studies highlight the impact of station allocation on (HSR) attractiveness. Similar to Psaraki and Abacoumkin (2002), Zhen, Cao, and Tang (2018) and Yang et al. (2019) explore the subject of access and egress, but now in the context of HSR-stations instead of airports. Both recognise the decreased attractiveness of HSR stations located on the urban outskirts due to increased access and egress times. Zhen, Cao, and Tang (2018) reveal, through path analysis of 2016 data from the Shanghai-Nanjing HSR corridor, that while the in-vehicle segment satisfaction is the primary driver of overall HSR satisfaction, access and egress satisfaction collectively hold a similar influence. Complementary, Yang et al. (2019) underscores the importance of all trip stages in determining HSR's attractiveness. The study focuses on access and egress mode choices of passengers in the Yangzi River Delta region (China), utilising data from a Fudan University HSR survey. The data from the HSR survey contains the access and egress modes choices of 1000 individuals in China. These results are valuable to this research on peripheral HSR-stations, since the lion's share of HSR-stations in China are located in peripheral areas. The research shows that PT is the most popular access mode with 62%, while the car, being either a private vehicle or taxi, has a share of 38%. This data is used for cross-checking assumptions on the European context in section 4.2, since China has previously been described as the prime example of a developed HSR-network and since it contains peripheral stations. The recommended best-practices of incorporating different trip segments in a long-distance mode choice model were also taken to heart in this thesis in chapter 3 and chapter 4.

The results of the search terms, provided in subsection 2.1.2, also included publications on station allocation that specifically align with this thesis' geographical scope and policy scope, namely the TEN-T network. These case studies concern a Swedish HSR-corridor (Hermelin and Gustafsson, 2022) and a Czech HSR-corridor (Kowalski, Marada, and Chmelík, 2023).

Hermelin and Gustafsson (2022) delve into the diverse impacts of HSR-development across Swedish cities, highlighting the importance of strategic planning and geographic context. This study examines local planning processes in four cities, uncovering the effects of Sweden's municipal policies in the strategic HSR planning. Sweden's approach concerning the East Link project, extending 160 km to the southwest as seen from Stockholm, contrasts with the typical European focus on first-tier cities for HSR infrastructure. Notably, this project includes stops in both larger cities and smaller settlements like Trosa, Nyköping, Norrköping, and Linköping, a remarkable strategy considering the modest population sizes of these areas. The project, initially scheduled for construction from 2019, has faced several timeline revisions, reflecting multi-level governance challenges. For example, in Linköping, the national government's decision to situate the HSR station at the edge of the city clashed with local preferences for a central station. This illustrates the trade-off dynamics between local and national interests.

Kowalski, Marada, and Chmelík (2023) describe similar trade-offs in Czech Republic. The context is that they address the necessary speed of the HSR link between Brno and Prague to make it a time-competitive alternative to car travel, factoring in access/egress times. This link, prioritised by the Czech government, forms a crucial part of the envisioned TEN-T network, as illustrated in Appendix A and Figure 2.2. The study includes a discussion on the newly proposed HSR-station in Brno, and its supposed disadvantageous passenger welfare effects for locals. Despite significant public opposition, Brno aims to move its central station one kilometre south with EU funding support, under the Europoint Brno project. This relocation, deemed "completely inappropriate" by Kowalski, Marada, and Chmelík (2023), is seen as detrimental to daily commuters and primarily beneficial for international traffic. Their research concludes that the prioritised Czech high-speed railway will be a time-competitive alternative to car travel only if some HSR services continue to operate from the current central station. This paper illustrates the trade-off between an alternative that is beneficial to the locals, maintaining Brno main station at its current location, and an alternative that is effective for traversing long-distance passengers, a relocation to the south-side of the city.

Both the publication of Hermelin and Gustafsson (2022) and Kowalski, Marada, and Chmelík (2023) feature complex governmental management of HSR-projects in which local and national interests clash.

This phenomenon was previously described by Marti-Henneberg (2015), who advocates that all government levels should converge in the decision-making on HSR-policies to prevent the ineffective allocation of HSR-stations.



Figure 2.2: The position of the Brno railjunction in the Baltic-Adriatic corridor and the Orient/East–Med Corridor (Municipality of Brno, 2023).

The phenomenon that local governments of relatively small towns succeed in lobbying for an HSR-station, as seen in the context of Sweden’s East Link Hermelin and Gustafsson (2022), is also observed in other parts of Europe. However, securing a station within the HSR network doesn’t necessarily guarantee access to HSR services (Moyano and Dobruszkes, 2017). This paper highlights that local and regional authorities often prioritise the acquisition of HSR infrastructure without considering essential operational aspects, like sufficient frequencies of line services to satisfy the demand of the local population. The study examines the situation of smaller cities along HSR routes through four European case studies from a service-oriented perspective. In addition, the paper provides empirical evidence that peripheral stations, or stations at the edge of a city, occur in Europe mostly along relatively small HSR-cities like Valence and Ciudad Real. The paper concludes that even cities with HSR infrastructure can be marginalized due to factors such as intermodal competition and limited market potential for train companies. Ultimately, similar to situations in Czechia (Kowalski, Marada, and Chmelík, 2023) and Sweden (Hermelin and Gustafsson, 2022), it boils down to balancing the interests of local residents with the efficiency of long-distance train travel for passengers. It is therefore advisable that individuals involved in such policy decision-making procedures are aware of the potentially conflicting interests.

As was discussed before in subsection 2.2.1, not all HSR-project are financially viable, which is why passenger welfare maximisation and externality minimisation are often applied as additional objectives. An example of welfare maximisation methodology is provided in the last entry of Table 2.5, being the paper by Roy and Maji, 2022 on HSR-station location optimisation. The method it proposes is very different than the simple economic model discussed in the analysis of (Banister and Givoni, 2013), but they both share the focus on public benefit, or welfare gain, through utility maximisation. The paper proposes a strategic mixed-integer linear model that can aid in the decision-making of the number of HSR-stations and its locations along an existing high-speed railway, taking into account matters like

fleet composition and line planning. This study may provide means to strategically locate stations along an existing line, but it does not provide the possibility of finding a strategic HSR-station location that includes redirecting the railways. This is a key observation that is utilised in the definition of the main knowledge gap in section 2.3.

2.3. Synthesis

This section concludes the literature review with a synthesis of the discussed literature. It combines the findings from subsection 2.2.1 and subsection 2.2.2 to create a synthesis that both identifies knowledge gaps and provides valuable information for subsequent chapters.

The literature analysis initiated with a number of publications on competition in long-distance travel. These findings illustrate a necessary condition to this research, namely that high-speed rail (HSR) can compete with air transport (AT) in the context of long-distance travel (Janić, 1993; Hensher, 1997; Wan et al., 2016). Although science is unanimous in this finding, the extent to which HSR can compete does vary per research. Milan Janić' research demonstrated through a cost minimisation model that HSR can effectively compete with AT over distances ranging from 400 to about 2000 km. While Román, Espino, and Martín (2007) deduce from recorded Chinese data that HSR dominates the modal split up until 500 km, and Adler, Pels, and Nash (2010) estimate that the real competition takes place up until distances of 750 km. In addition, Román, Espino, and Martín (2007) estimates a potential maximum market share for HSR of 35% under favourable conditions on the Madrid-Barcelona corridor. Scientists may be divided on the extent to which HSR can compete, but it can be concluded that the overlapping market for HSR and air transport will become increasingly large (Wang et al., 2015). This increase in competition is fueled by the fact that they both tend to serve areas with high population densities and well-developed economies.

The extent to which HSR can compete with AT, but also with car, as a long-distance mode is often estimated through the use of mode choice models (Román, Espino, and Martín, 2007; Wang et al., 2015). The mode choice models that are most used in literature for estimating long-distance mode choice behaviour are logit models, which assume that individuals are rational decision-makers that aim to maximise their decision utility. The commonality of such models is clearly visible in both Table 2.3, Table 2.4 and Table 2.5. However, a fundamentally different type of model is also used in literature by Donners (2016), Grolle et al. (2024) and Borgogno (2023), who all apply a regret minimisation model. An elaborate consideration between the two types is provided in chapter 3, which is the methodology chapter of this thesis.

In applying such a mode choice model, Zhen, Cao, and Tang (2018) recommend to take the differences between the trip components of a long-distance trip into account. Zhen, Cao, and Tang (2018) illustrate how the in-vehicle segment is the primary driver of overall HSR satisfaction, while access and egress satisfaction collectively hold a similar influence. This implies that time is not experienced uniformly across the different components. This recommendation by Zhen, Cao, and Tang (2018) was taken to heart in the formulation of chapter 3 and chapter 4. An additional, valuable conclusion from literature on mode choice models was provided by Zhang, Yang, and Wang (2017), who demonstrate that long-distance mode choice is mainly dependent on travel cost and travel time, and less so on frequency.

In addition to quantifying the modal splits after HSR-investments, which usually generates a modal shift of passenger that opt for HSR, the literature study also highlights another 'significant' group of new rail passengers after construction (Hensher, 1997). This additional group of new passengers are defined as induced demand, which refers to newly generated demand as a result of increased supply of infrastructure (Hensher, 1997; Chen et al., 2016; Jiao, Wang, and Jin, 2017; D'Alfonso, Jiang, and Bracaglia, 2016). Literature shows that induced demand volumes are substantial, varying from 6% to 37% of the total HSR-ridership. The potential side-effects of induced demand after HSR-construction were illustrated by Chen et al. (2016). Their publication describes how the expansion of the Chinese HSR-network, while boosting the economy and social welfare, also led to an increase in GHG emissions. This increase was attributed to the effect of induced demand, since the train is the least polluting mode per distance and HSR-expansion would therefore lead to a decrease in GHG emissions if modal

shift was the only contribution to HSR-ridership change.

Another frequently discussed topic in literature on high-speed rail is profitability. Revenues are often not sufficient in providing a positive cost-benefit ratios (Hensher, 1997), but welfare and environmental effects of HSR-investments are commonly positive (Jiao, Wang, and Jin, 2017). This is why many HSR-investments are defended on welfare and environmental grounds (Proost et al., 2014). Including these effects is possible through the appliance of an SCBA, which allows for both financial and non-financial effect. Including welfare benefits and environmental externality reduction does however not guarantee a positive cost-benefit ratio, which was shown by Proost et al. (2014) and Bröcker, Korzhenevych, and Schürmann (2010). One can conclude that it is often a close call whether HSR projects add value to an economy. In addition, Adler, Pels, and Nash (2010) recommend to apply a comprehensive network model when estimating welfare effects to accurately incorporate aggregate effects.

Wan et al. (2016) describe China's network as the prime example of a modern HSR-network. The difference with Europe's HSR-network is not only its size, but also in its station allocation (Banister and Givoni, 2013; Zhen, Cao, and Tang, 2018). HSR-stations in Asian countries, like China, are often detached from the city center and located in the periphery. While in Europe they are mostly located within the 'natural' boundaries of a city, with most of the exceptions being in France. Currently, more than 60% of the regions in Europe that are accessible by HSR are connected through use of a centrally-located station (Wenner and Thierstein, 2022). It is hypothesised that this remarkable difference between Europe and China stems from the fact that China has experienced rapid urbanisation over the last decades, while many stations in Europe are historic and have seen the city develop around it.

These striking differences are discussed in, among others, the paper of Banister and Givoni (2013). This article provided a clear distinction of HSR-station typology, namely a 'city-centre' and a 'city-outskirt' location. In the case of the 'city-outskirt' option, Banister and Givoni (2013) advise to integrate the HSR-station with existing airports to maximise accessibility, which is in-line with research conclusions of Malott (2022) and Bruno (2022), who recommend intermodal connections to create an accessible and developed HSR-network. The literature study also provided two examples of station classifications that are based upon population density (Wenner and Thierstein, 2022; Marti-Henneberg, 2015), which inspired the definitions of 'central', 'urban' and 'peripheral' in the key definitions list of section 1.7. This thesis often refers to the 'city-outskirt' station definition of Banister and Givoni (2013) as a peripheral station.

Banister and Givoni (2013)'s research on HSR-stations also provided another valuable recommendation to this research. The article states that not only station allocation is a pivotal factor, but also that the number of stations is pivotal. They advise that most European cities should not have more than one HSR-station due to the levels of demand for travel. In addition, it is argued that new HSR-station locations should be well-embedded in public transport networks and that this should play a large role in the decision-making process (Wenner and Thierstein, 2022). Psaraki and Abacoumkin (2002) phrase a similar stance even more strongly, stating that an efficient access system is a prerequisite for the functioning of peripheral airports, which is assumed to also apply for peripheral HSR-stations.

The topic of decision-making on HSR-station allocation is also featured in literature. Marti-Henneberg (2015) argues that government levels should converge in the decision-making on HSR-policies to prevent the ineffective allocation of HSR-stations. This statement originates from the fact that local, regional and national interests may clash in the allocation of HSR-stations, as was seen in the studies of Hermelin and Gustafsson (2022) and Kowalski, Marada, and Chmélík (2023). Ultimately, it boils down to balancing the interests of local residents with the interests of long-distance travellers (Moyano and Dobruszkes, 2017).

These conflicting interests arise from the fact that there are both positive and negative effects of allocating an HSR-station in the city-outskirts. Allocating an HSR-dedicated station to a city-outskirt may lead to poorer accessibility of the HSR-services and sometimes a disconnect between conventional train services and high-speed services, but it can also lead to lower travel times for traversing passengers. These benefits and losses can be split up in two categories, namely direct transport effects and

non-transport effects Banister and Givoni (2013). They state that there is a case for the construction of a new station if the reduction in access cost (direct transport effects) is larger than the construction costs of the station and its corresponding infrastructure plus the time loss of those rail passengers only passing through the station.

The last entry of Table 2.5 illustrates the role of passenger welfare effects of HSR-station allocation in the economic appraisal of such infrastructure investments once more (Roy and Maji, 2022). This paper on HSR-station allocation applies an optimisation method to find strategic locations along existing railways. The applied method is more complex than the suggested approach in Banister and Givoni (2013), but both emphasise the inclusion of passenger welfare effects in the decision-making on HSR-station allocation. This focus on passenger welfare effects as a decisive factor in HSR-investments is a frequently recurring theme throughout this literature review (Banister and Givoni, 2013; Proost et al., 2014; Jiao, Wang, and Jin, 2017; Roy and Maji, 2022).

Much research has been retrieved on the topic of high-speed rail. Mostly on high-speed trains as a competing mode for long-distance travel, but less on the allocation of HSR-stations. One can however extract knowledge gaps while reading between the lines of section 2.2. The two identified knowledge gaps are specified below. The first one concerns a knowledge gap that is research focused, while the second is more of a practical nature.

Knowledge gap 1: Quantitative research on the passenger welfare trade-off between central and peripheral HSR-stations is lacking

Strategic allocation of high-speed rail infrastructure is a recurring topic in literature, as seen in Borgogno (2023) and Roy and Maji (2022). Their HSR-station allocation constraints however exclude the possibility of peripheral HSR-stations, which contributes directly to the identification of this knowledge gap. The conclusions of Borgogno (2023) suggest where to strategically build high-speed rail infrastructure between urban nodes, but not where to strategically build stations along these strategically generated edges, explicitly assuming that the stations are located centrally in the urban nodes. In contrast, Roy and Maji (2022) do provide means to strategically locate a station along an existing line, but do so in the urban area of Tokyo. The exclusion of peripheral stations as a full-fledged option is remarkable since the prime example of a developed HSR-network, being the Chinese network, contains mostly peripheral stations (Wan et al., 2016; Banister and Givoni, 2013; Zhao, Wu, and Shi, 2021). In contrast, the lion's share of European stations are located in city centres (Wenner and Thierstein, 2022). A situation that is assumed to remain the same in a number of publications that model a future European network (Donners, 2016; Grolle et al., 2024).

In conclusion, research suggests that passenger welfare benefits can be generated by relocating HSR-stations to the city outskirts (Banister and Givoni, 2013). However no research is available that quantitatively assesses the extent to which passenger welfare benefits can occur when relocating high-speed rail services from centrally-located stations to city-outskirt stations, nor under which conditions they occur. This is why knowledge gap 1 states that quantitative research on the passenger welfare trade-off between central and peripheral HSR-stations is lacking. A comparable knowledge gap has previously been defined at a national level by Manuel Weiß and Münter (2022), stating that there is a deficit of quantitative studies on socioeconomic effects of HSR-station allocation in Germany.

Knowledge gap 2: Traffic forecasts for rail passenger distribution on the future European railways, as envisioned in recent EU policies, are unavailable in literature

Many models that assess the competition between High-Speed Rail (HSR) and other modes were discussed in subsection 2.2.1. This varied from models that assessed case studies to models that assess the future TEN-T network in 2030 (Donners, 2016). Although policy plans exist for the development of the European railways up until 2050 (European Commission, 2021b), no forecasts are available in literature that estimate the future passenger distributions over that envisioned European network for prediction years later than 2030. Both academic and non-academic studies exist that model hypothetical networks for 2050 (Borgogno, 2023; PTV Group, 2023), but no source is available that estimates the passenger distribution of the envisioned 2050 TEN-T network.

Finally, an ancillary aim of this literature study was to identify data sources for use in succeeding chapters, since this field of study is notorious for a lack of data. This chapter achieved this aim through multiple publications. Examples include the publication of Donners, 2016, containing an estimated modal split and European urban node data set, Bruno, 2022, containing data on transfers per railway journey, and Grolle et al., 2024, containing estimated long-distance passenger demand volumes between urban nodes in Europe. Lastly, Chinese data from Yang et al. (2019) is used for cross-checking assumptions on the European context in section 4.2,

3

Methodology

This chapter provides the necessary methodological steps that were executed for this research. It starts off with a research framework in section 3.1, visualised in Figure 3.1. This framework and the accompanying paragraphs guide the reader through the steps that were taken in this research and highlights the three essential methods that were used to acquire the wanted results. These three essential methods are then discussed in section 3.2, section 3.3 and section 3.4.

Note that this chapter only discusses the methodology that was used in this research. Subsequent chapters describe how input data is gathered and specified, and how they are specifically implemented.

3.1. Research Framework

The research framework that was applied in this research is shown in Figure 3.1. It contains three different parts that were executed in consecutive order. Every part corresponds to one of the three following chapters, and every main method to one of the three subsequent sections in this methodology chapter. Some smaller methodological steps, that were implemented in addition to the three main methods, are elaborated on in the paragraphs below. The upcoming paragraphs also highlight when in the framework a sub-question from section 1.6 is answered.

Part I: Long-Distance Travel in Europe 2050

The main method of Part I in Figure 3.1 is the combined mode-route choice transport model, but it is referred to throughout this thesis as the transport model. This method is defined in section 3.2. The application of this method leads to a passenger distribution per mode and per link over a transport network. It was applied in this thesis on the case of long-distance travel in Europe per 2050, as the name of the corresponding chapter 4 suggests.

Almost all steps visualised in Figure 3.1 for Part I are elements of the transport model or provide input for that method. The only element which is not associated with this is the box labeled "Induced Demand". Induced demand is one of the origins that is expected to cause an increase of rail passenger volumes between the base year and the prediction year. In total, the increased passenger volumes at railway edges can be attributed to three causes (PTV Group, 2023):

- Autonomous growth, which extrapolates 'existing traffic' to 'predicted traffic';
- Modal shift, which generates additional 'diverted traffic';
- Induced demand effects, which generate additional 'induced traffic'.

The effect of autonomous growth is accounted for in the top-right corner of Part I Figure 3.1. It is the extrapolation of passenger distribution data from the year in which data was recorded to the prediction year. The reason that the year 2019 is used here instead of the base year (2024) has to do with the availability of the data, as will be discussed in chapter 4. The increase of passenger volumes due to a modal shift is inherently accounted for in the combined mode-route choice model.

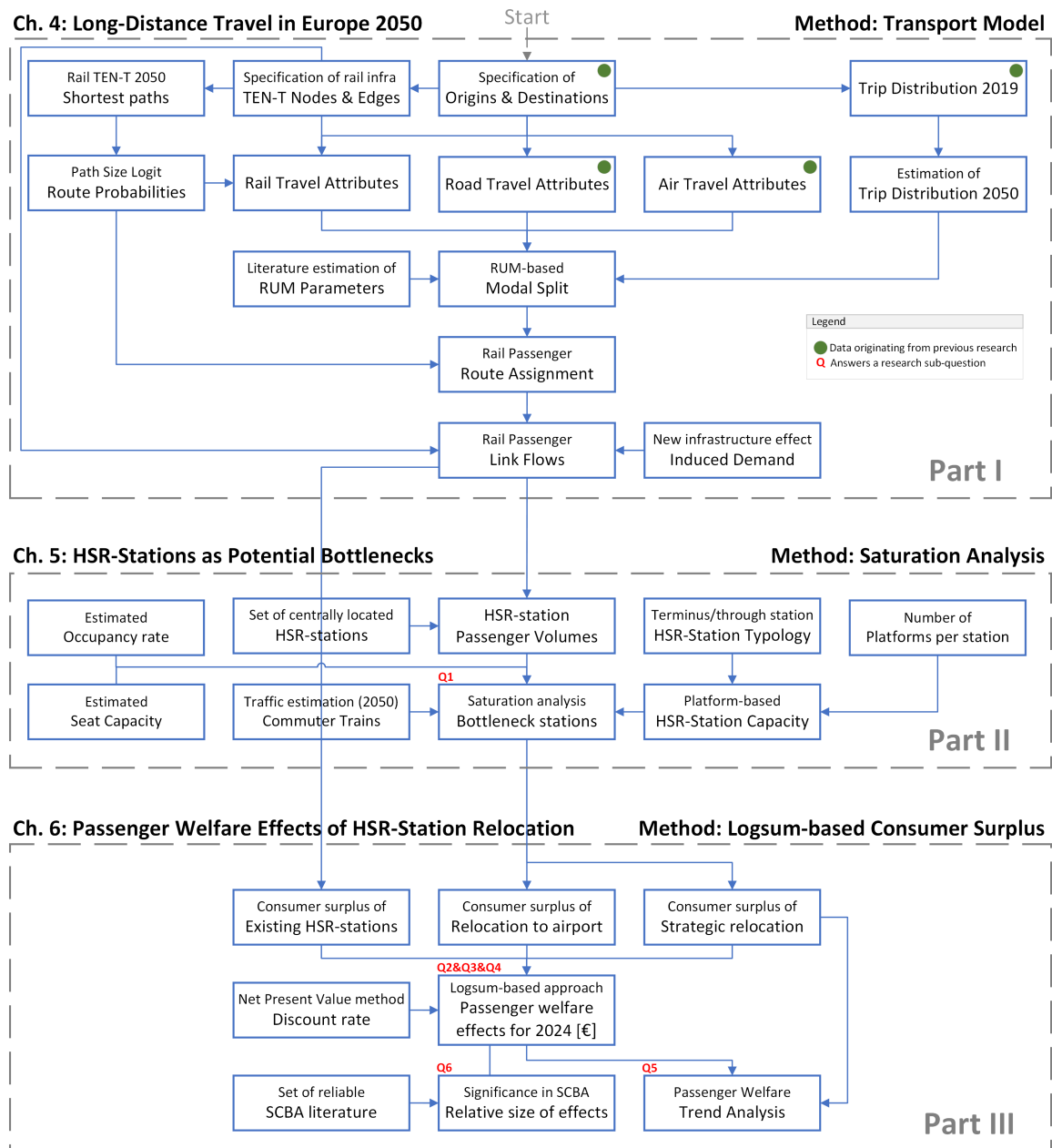


Figure 3.1: The research framework. The letters in red visualise when results to answer a sub-question (Q) are acquired. Created with Visio (Microsoft, 2018).

The effect of induced demand, on the other hand, is not incorporated in the mode-route choice model. It has however previously been described in the literature study chapter 2 as a substantial share of the passenger volumes that use new infrastructure, which is why it was included in this research with many new railway elements. A multiplier for induced demand was therefore applied on passenger volumes that use newly constructed railway infrastructure. The value of the multiplier is assumed in chapter 4, and matches the discussed multiplier range of from the literature study (D'Alfonso, Jiang, and Bracaglia, 2016).

The first part of Figure 3.1 does not directly answer one of the five sub-questions, but it does provide necessary input to eventually answer them. Not only for Q1, but the combined mode-route choice model is iterated, with adapted input, in Part III of Figure 3.1 to answer Q2, Q3 and Q4.

Part II: HSR-Stations as Potential Bottlenecks

The main method of Part II in Figure 3.1 is the saturation analysis. All elements of Part II are related to this method and are elaborated on in section 3.3. The application of this method generates saturation levels for the HSR-stations it assesses. Essentially, the method defines whether there is capacity left at an HSR-station or whether it is a bottleneck. The necessary input exists of the results of Part I and various other data sources. By identifying potential bottlenecks, it answers Q1.

Part III: Passenger Welfare Effects of HSR-Station Relocation

The main method of Part III in Figure 3.1 is the Logsum-based Consumer Surplus method (Ben-Akiva and Bierlaire, 1999). This method is discussed and mathematically defined in section 3.4 in coherence with the Net Present Value method (Kowalski, Marada, and Chmelík, 2023). This method was applied to answer sub-questions Q2, Q3 and Q4, and to provide input for Q5 and Q6. The approach to generating the HSR relocation alternatives, and other experiment set-up details, are discussed in chapter 6.

For Q2, the passenger welfare effects of existing peripheral HSR-stations were quantified. This was done by running the base-model, containing the TEN-T 2050 network with both a central and peripheral station, running a scenario without the peripheral stations ('only central') and a scenario without the central stations ('only peripheral'). Further context is provided in chapter 6, but this brief elaboration is useful for the interpretation of this methodology section.

Answering the next two sub-questions required the generation of hypothetical networks. The generation approach is shortly illustrated here to provide context: Suppose that the saturation analysis identifies the centrally-located HSR station Hannover Hauptbahnhof as a bottleneck. The consequence for this study is that the HSR-services will now be relocated through two different approaches. The first one being a relocation to a nearby airport, and the second one being a relocation to a strategic location that maximises passenger welfare. Answering Q3 means that, in this case, an HSR-station is created at Flughafen Hannover-Langenhagen and that infrastructure is redirected to include this station in the network. Answering Q4 requires multiple experiments per city to find the most strategic HSR-station location out of a certain experiment set. The transport model that is created in Part I is iterated for every HSR-service relocation experiment to quantify passenger redistribution and passenger welfare effects. The heuristic approach to generate these alternatives is detailed in chapter 6, since it does not include any additional scientific methodologies that belong in this chapter.

The results from Q2 to Q4 provide input to do a trend analysis on the efficiency of peripheral HSR-stations to generate passenger welfare benefits. This analysis answers the previously established sub-question Q5. Finally, the results are used to assess the relative significance of passenger welfare effects in SCBAs for economic appraisal (Q6).

3.2. Transport Model

This thesis employs a combined mode-route choice model to estimate the passenger distribution over the Comprehensive TEN-T in 2050 (Dios Ortúzar and Willumsen, 2011). The combined mode-route choice model is an adapted version of the 4-step transport model, which was discussed previously in the context of the research by Donners, 2016 in the literature study. Both are aggregate models, meaning that they concerns travel flows instead of disaggregate individual trips, but the combined mode-route choice model allows for passengers to take various routes between OD-pairs. This method was selected to facilitate having multiple rail paths between OD-pairs, thus adding realism to the model. The argumentation for having multiple rail paths and thus a probabilistic assignment is discussed later in the subsection 3.2.3.

To see how these two methods compare, this introduction starts off by listing the four subsequent steps of the 4-step transport model. These are:

1. Trip Generation: The number of trips that a city node attracts and produces per time frame.
2. Trip Distribution: Distributed traffic flows between Origin-Destination (OD) pairs.
3. Modal Split: The mode choice probabilities per OD-pair.

4. Route Assignment: Route probabilities and passenger volumes per route of a certain mode between OD-pairs.

The 4-step transport model is per definition sequential. It is therefore essential that mode attributes have to be known before calculating the mode choice probabilities per OD-pair. However, when including multiple rail routes for realism, the average rail mode attributes depend on the probabilities of rail passengers to select those routes, which is essentially the route assignment step. Adaptation of the 4-step transport model is therefore necessary to realise the inclusion of route probabilities in the mode attributes. This effectively transforms the 4-step transport model to a combined mode-route choice model, which is presented visually in Figure 3.2. Section 3.2.1 elaborates why the trip generation step is excluded from the transport model and thus from this overview.

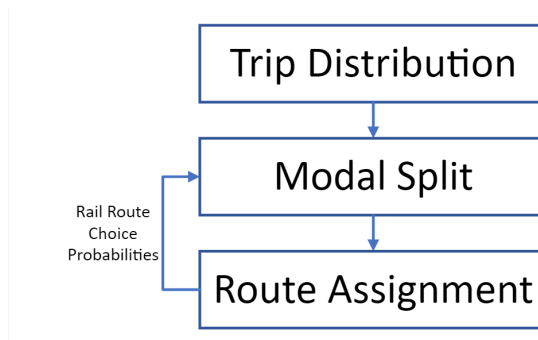


Figure 3.2: The combined mode-route choice model as applied in this study. Created with Visio (Microsoft, 2018).

3.2.1. Trip Generation

Trip generation, the initial phase of the 4-step transport model, involves quantifying the potential trips generated and attracted by each city or urban node per time frame. This initial step often assumes that production equals attraction, meaning that there is symmetry in the city's inflow and outflow.

Donners (2016) and Borgogno (2023) perform this step by assuming that the average European makes 9 long-distance trips per year, then calculating the average willingness to travel per city node based on income (GDP per capita) and multiplying this value per the population of each city node. By doing this they reflect the influence of income on long-distance travel willingness per region and account for the difference in long-distance vs short-distance trips. Grolle et al. (2024) opts for another approach, based on European air travel data, which is further elaborated on in subsection 4.4.1.

Transport modellers can apply growth factors if applicable production and attraction values are readily available, but do not match their prediction year. The same is true if an applicable OD-matrix with distributed trips is available. The latter is the case for this research, which is why the trip generation step was excluded from this study, effectively creating the combined mode-route choice model as presented in Figure 3.2. The exclusion of the trip generation step means that the results of the transport model in section 4.4 initiate with the Trip Distribution results.

3.2.2. Trip Distribution

The first step of the combined mode-route choice model distributes trips between the OD-pairs of a transport network for the prediction year. The output is therefore an OD-matrix containing passenger volumes per time frame (Dios Ortúzar and Willumsen, 2011). A regularly used method for this step is the gravity model. Both Donners (2016) and Borgogno (2023) apply a form of the gravity model, respectively a single and a doubly constrained gravity model. Another method was applied by Grolle et al. (2024), who used airport traffic data from 2019 in combination with estimated market shares for air per distance unit, from Donners (2016), to craft a refined OD-matrix.

As mentioned in the previous section, it is common practice to use growth factors on applicable OD-matrices when they are available. Three different OD-matrices concerning European long-distance travel are available for extrapolation. section 4.4 describes which one was most applicable to this re-

search and therefore selected. The equation for adding the growth effect is shown in Equation 3.1 (Dios Ortúzar and Willumsen, 2011). The autonomous growth rate g was acquired from literature.

$$p_{ij}^{2050} = g \times p_{ij}^{T_0} \quad \forall i, j \in N \quad (3.1)$$

where: p_{ij}^{2050} = Passenger demand between nodes i and j in the prediction year 2050
 g = Autonomous growth rate for the whole geographical scope
 $p_{ij}^{T_0}$ = Passenger demand between nodes i and j in base year T_0 of the dataset

After extrapolating the OD-matrix it is assumed to be inelastic, or in other words: exogenously defined. No functions are available in the combined mode-route choice model that provide "travelers" to opt-out or change in destination choices. The trip distribution matrix will remain the same. The only additional effect on passenger volumes which is incorporated in this research is the effect of induced demand, as has been elaborated on in the beginning of section 3.1. This was added for new rail infrastructure elements after the last step of the transport model, namely after the route assignment. Further elaboration on induced demand is provided in section 4.4.

3.2.3. Modal Split

Selection of mode choice model

Chapter 2 shows that various choice models are used in the literature to model travel choice behaviour on the long-distance. Examples of these are Mixed Logit (Lee, Yoo, and Song, 2016) and the standard Multinomial Logit (Hensher, 1997; Adler, Pels, and Nash, 2010). The results that are presented in this report follow in the footsteps of the latter two researches and were acquired through a Random Utility Maximization's linear-additive MNL-model. The argumentation for this selection is provided in the subsequent paragraphs.

Two of the discussed theses in chapter 2, namely Donners (2016) and Borgogno (2023), use not Random Utility Maximisation (RUM) but Random Regret Minimisation (RRM) as a mode choice model. The choice model of Random Regret Minimisation that they use originates from Chorus (2010) and assumes that when choosing between alternatives, people anticipate and aim to minimize regret. The underlying theory assumes that people do not care about absolute levels of choice attributes, like travel time and travel cost, but about relative levels of choice attributes. Put differently, the preferences of people are assumed to be choice-set dependent. In addition, losses loom larger than gains in RRM. This leads to the RRM characteristic that the "in-between" option has a relatively high choice probability in comparison to RUM.

Chorus (2010) shows in his paper that RRM performs slightly better in an ex-ante prediction of mode- and route choice behaviour than RUM. Donners (2016) states in his thesis that he calibrated his generated trip dataset with available market shares through using RUM and RRM. He concludes that RRM fits the market shares better, especially on the shorter distances. One can however not verify his RUM-model since the sensitivity (i.e. choice parameter) for the single included attribute, travel time, is not provided. Nor is it known whether he used any Alternative Specific Constants (ASC). Borgogno (2023) adopts RRM as choice modelling approach on the same basis as Donners (2016).

The logical follow-up question is then why this research assumes RUM as a decision-rule for mode choice, while RRM is in some transport cases better in predicting choice behaviour. This choice is essentially a trade-off between behavioural relevance and passenger welfare analysis with sound economic underpinning. The trade-off is decided in favor of applying RUM for the following arguments:

Argument 1: Quantification of passenger welfare effects needs RUM

Section 3.4 describes how the Logsum-based Consumer Surplus method is the most fitting method for the objective of this thesis, i.e. quantifying passenger welfare effects of relocating HSR-services to dedicated train stations in the city outskirts (Ben-Akiva, 1985). The section describes how the Logsum method is grounded in the principles of discrete choice theory. The consequence of this is that the Logsum method needs the so-called systematic utility, as defined by the RUM method, as input. In addition, the Logsum can only be used if the unobserved component of utility is an independently and identically distributed extreme value (De Jong et al., 2006), which is per definition not true for RRM

since it violates the i.i.d. requirement. This makes it impossible to directly adapt the Logsum method to an RRM-based welfare analysis.

Since RRM has become common as a model for choice behavior, with good results, the demand for modeling the consumer surplus with these results has indeed grown. This has led to the proposed method of Dekker and Chorus (2018). The disadvantage of this proposed method is that it is only able of quantifying surplus change if there is one altered alternative with regards to its non-price related attributes, while the others remain the same. Both the violation of the i.i.d. requirement, meaning that alternatives are not independent, and the absence of a marginal regret of income prevent the possibility of quantifying the net welfare changes when multiple alternatives change. This is an issue for this thesis, since multiple alternatives simultaneously in the experiments of Q3. It is assumed in these experiments that relocating the HSR-services to the airport changes the access and egress times of both the air and rail mode. On top of this, Dekker and Chorus (2018) only advise to use this method as a second-opinion model for the appraisal of infrastructure in policy making.

In conclusion; The Logsum has proven its worth in many practical applications and theoretical exercises. Applying it in coherence with the RUM model is relatively straightforward. While the RRM-based welfare analysis has many limitations and lacks axiomatic (theoretical) underpinning. RRM effectively lacks a common money metric to transform differences in regret in a monetary passenger welfare change. It is for this reason concluded that the quantification of passenger welfare effects needs RUM, a model that is more suitable for economic valuation. More information on the use of the Logsum method to estimate the passenger welfare can be found in section 3.4.

Argument 2: The average person's choice behaviour is more similar to RUM

Some literature shows that RRM performs slightly better (Chorus, 2010 Donners, 2016), and some literature shows that RUM performs slightly better in the prediction of travel choice behaviour. The paper by Hess, Stathopoulos, and Daly (2012) is a well-known one in the latter category, with hundreds of citations. This paper explores respondent heterogeneity in choice modeling, questioning the assumption that all individuals follow homogeneous utility-maximizing decision rules. It introduces a latent class model that accommodates differences in decision-making paradigms within a single dataset. Hess, Stathopoulos, and Daly (2012) demonstrate through case studies that incorporating a mix of decision rules significantly improves model fit, suggesting that observed taste heterogeneity may actually reflect differences in decision-making strategies.

It is usually assumed that mode choice of a sample of individuals is completely generated by one decision-rule or another (in this thesis: utility-based). While Hess, Stathopoulos, and Daly (2012) assume that some people's choices may be reflected by one decision-rule and other people's choices may be reflected by a different rule. Their work highlights – using latent class-analyses – that a share of 20% up to 40% regret-minimisers may exist in a sample where utility-based models provide the better overall fit with the data. Thus implying that the average person's decision-making process is closer to a RUM model than to an RRM model.

Formulation of the RUM model

Random Utility Theory assumes that a decision-maker will choose, in a fully rational way, the alternative i from a set of I alternatives if the random utility U_i is larger than the utilities of the other alternatives in the set (McFadden, 1972). This random utility contains two elements. The first is a deterministic utility V_i , sometimes called systematic utility, that can be related to all observed factors. These observed factors are described as M attributes x_m . The second element of the random utility is a random error term ϵ_i , which can be interpreted as the unknown factors that influence the decision-makers utility. This includes not only unobserved factors, but also randomness in decision-making and heterogeneity among the decision-makers. The most simple and general formulation of the utility function is then the following, with β_m being the taste-parameter of attribute m :

$$U_i = V_i + \epsilon_i = \sum_{m=1}^M \beta_m x_{im} + \epsilon_i \quad \forall i \in I \quad (3.2)$$

After acquiring utilities per alternative in the choice set, one can predict choice behaviour up to a certain probability. These probabilities can be acquired under the assumption that ϵ_i is identically and independently distributed (i.i.d.) as an Extreme Value Type I across all alternatives and that the variance equals $\frac{\pi^2}{6}$. If this assumption holds, then the probabilities can be calculated in the following way:

$$P_i = \frac{\exp(V_i)}{\sum_{j=1}^J \exp(V_j)} \forall i \in I \quad (3.3)$$

This thesis also includes alternative specific constants (ASC) as ASC_i . These ASCs are incorporated in the deterministic utility and represent the utility that is associated with factors other than the observed attributes (Willumsen et al., 2001). The ASCs should be part of every alternative, except for a single reference alternative ($ASC_{ref} = 0$). This is the conventional approach in literature since only differences in utility matter. Furthermore, every ASC should have a theoretical underpinning, meaning that one can understand its negative or positive influence.

According to literature, travel cost and travel time are the most relevant attributes for long distance travels (Zhang, Yang, and Wang, 2017). Other studies like Lee, Yoo, and Song (2016) also take service frequency into account as an attribute, but Zhang, Yang, and Wang (2017) have illustrated that service frequency only plays a small role in the context of long-distance travels and competition between rail and air travel. Since this study is about the infrastructure in 2050, and it is speculative to assume what the services will be, frequency is not included as an attribute. All other potential variables, like safety or duty-free shopping (Lee, Yoo, and Song, 2016), are excluded due to their limited influence in predicting mode choice behaviour.

Combining the selected attributes with the mode choice set generates the utility functions in Equation 3.4, Equation 3.5 and Equation 3.6. The mode choice set was defined previously in section 1.7.

$$U_{\text{rail}} = \beta_{TC} \times TC_{\text{rail}} + \beta_{TT} \times TT_{\text{rail}} \quad (3.4)$$

$$U_{\text{air}} = ASC_{\text{air}} + \beta_{TC} \times TC_{\text{air}} + \beta_{TT} \times TT_{\text{air}} \quad (3.5)$$

$$U_{\text{car}} = ASC_{\text{car}} + \beta_{TC} \times TC_{\text{car}} + \beta_{TT} \times TT_{\text{car}} \quad (3.6)$$

All choice parameters β_m and most of the attributes were retrieved and adapted from scientific literature and their corresponding datasets and models. The rail attributes were however generated by using a combination of software packages (QGIS, 2023; NetworkX, 2023; Python Software Foundation, 2024), in which the 2050 TEN-T network was simulated. For quantification and elaboration, see section 4.2.

Formulation of the travel time attribute

The travel time TT is defined as an aggregated Travel Time. Equation 3.7 was applied to accurately capture the different stages of a long-distance trip, with the door-to-door journey being split up into access, waiting times, in-vehicle time, egress time and transfer times. Ramjerdi (2015) argues that a single quantification for the value of time does not reflect reality in long-distance travel, which aligns with the view of Zhen, Cao, and Tang (2018) in chapter 2. This is why this study assigns different weights to different trip components in chapter 4. These weights ω , taste parameters β and Alternative Specific Constants ASC_{mode} are quantified and discussed in subsection 4.3.3.

$$TT_{\text{mode}} = \omega_{\text{acs}} \cdot T_{\text{acs}} + \omega_{\text{wai}} \cdot T_{\text{wai}} + \omega_{\text{inv}} \cdot T_{\text{inv}} + \omega_{\text{trf}} \cdot T_{\text{trf}} + \omega_{\text{egr}} \cdot T_{\text{egr}} \quad (3.7)$$

Generation of the rail route choice set

The transport model generates multiple rail routes per station-pair to capture a range of realistic route choices that passengers might consider, thereby increasing realism. This decision was also made to prevent, to some extent, that unrealistically high passenger loads are assigned to certain links. This model uses an uncapacitated route assignment since the future capacities of railways are unknown, but by distributing over multiple routes it is less likely that the actual capacities were exceeded in the model.

According to Fiorenzo-Catalano, Van Nes, and Bovy (2004), choice sets can be generated using various approaches, such as labelling, which involves identifying routes that are optimal in terms of different

travel attribute criteria. The paper by Fiorenzo-Catalano, Van Nes, and Bovy (2004) also includes other approaches, like the multi-objective (multi-label) approach or the k-shortest path approach, but this research has selected the simpler labelling approach. This decision was made due to the computational limitations of the NetworkX (2023) package in Python Software Foundation (2024), which does not include a function that allows for multi-objective shortest path problems. The possibility of generating k-shortest paths with NetworkX was dismissed due to having too long computation times for facilitating relocation iterations of the transport model. A second reason for removing k-shortests paths from the equation was the extremely limited difference in the paths due to the dense network. See for more information on that trade-off the discussion of the shortest paths in section 4.4.

The labels that were used for the single-objective shortest path approach represent the attributes and disutility per railway edge in accordance to the negative of the utility function of Equation 3.4. Effectively, this means that the labels time, distance, and disutility were used. The label disutility was used instead of utility since the NetworkX function only allows to minimise positive values and the U_{rail} is per definition always negative. The generation of this set of alternative rail paths per station-pair allowed for creation of a comprehensive set of paths per city-pair (OD-pair), providing a robust basis for the following steps.

Estimation of the rail attributes

Combining the probabilistic assignment method called Path Size Logit, described in the upcoming subsection 4.4.3 on route assignment, with the rail utility function in Equation 3.4 leads to route choice probabilities. This step was executed prior to determining the modal split, because the route choice probabilities were necessary for finding an averaged TC_{rail} and TT_{rail} . The overview of these steps has been provided in the combined mode-route choice model schematic of Figure 3.2.

After generating the route choice probabilities for rail route alternatives, the calculation of the averaged TC_{rail} and TT_{rail} was done according to Equation 3.8 and Equation 3.9 for the R number of routes per OD-pair. This value R can vary per OD-pair since one to three paths are generated per station pair, depending on the network between them, and since many cities (ODs) contain multiple stations, thus leading to a set that can be many multiples of three.

$$TC_{\text{rail}} = \sum_{i \in R} P_i^{\text{PSL}} \cdot TC_{i,\text{rail}} \quad (3.8)$$

$$TT_{\text{rail}} = \sum_{i \in R} P_i^{\text{PSL}} \cdot TT_{i,\text{rail}} \quad (3.9)$$

Mode choice probabilities

The probability-weighted rail attributes were then used together with attributes of the airplane and car mode to generate the utilities per OD-pair with the formulae of Equation 3.6, Equation 3.5 and Equation 3.4. These utilities then served as input for Equation 3.3, which is how the mode choice probabilities per OD-pair were found. This concludes the modal split methodology section.

3.2.4. Route Assignment

The aim of the route assignment step is to generate realistic route choice probabilities and, by doing so, the link flows per route per OD-pair. However, applying the MNL probability function of Equation 3.3 on the three generated paths may very well be a violation of the assumed independence of alternatives where MNL is based on. If overlap exists between paths, and that chance is very high, then the route alternatives are no longer independent (Hoogendoorn-Lanser and Bovy, 2007). The practical consequence of applying MNL in a case with much overlap is that routes that are nearly similar are treated as completely independent alternatives, and are therefore both assigned an unrealistically high probability, and a very different alternative with a slightly worse utility might be under-performing. A well-known example of the interdependence of alternatives in choice models is the red-bus/blue-bus network (Ben-Akiva and Bierlaire, 1999).

To account for the similarities in a route choice set, one could apply various choice models that deal with these similarities in their own respective ways. Those considered were Mixed Logit, Nested Logit,

and Path Size Logit (Ben-Akiva and Bierlaire, 1999). Mixed Logit was removed from this consideration since it is not very well suited for economic appraisal (Chorus, 2021). The Nested Logit approach could also have been suitable but no fitting nest parameters for a similar context of long-distance rail travel could be found in the literature. This left the Path Size Logit model as the only applicable option, but it is also a very well-suited option for three reasons. One; it explicitly accounts for the overlap between rail paths, providing a more realistic representation of traveler behavior in networks with shared segments. Two; It fits well with the logsum-based approach for economic appraisal, since it uses as input the same systematic utilities as that method. Three; The PSL method does not require additional parameters, unlike the two other discussed options. This eliminates the uncertain effort of estimating an additional parameter and therefore decreases the room for error.

In conclusion, a Path Size Logit model was applied to account for the degree of overlap between the set of shortest paths for every OD-pair, i.e. city-pair, in the rail network. The probability function of the PSL by Ben-Akiva and Bierlaire (1999) is defined in Equation 3.10. Set R contains all rail route alternatives i per city-pair:

$$P_i^{PSL} = \frac{\exp(V_i + \ln(PS_i))}{\sum_{j \in R} \exp(V_j + \ln(PS_j))} \quad \forall i \in R \quad (3.10)$$

where: P_i^{PSL} = Probability of a rail passenger to select rail route i
 i = Route i in set R
 R = Set of rail route alternatives per city-pair; V_i
 PS_i = Path Size factor for route i

The Path Size factor is calculated per route i as presented in Equation 3.11. The cost elements in this function correspond to the distance in kilometers, since PSL is concerned with the physical overlap of paths (Hoogendoorn-Lanser and Bovy, 2007).

$$PS_i = \sum_{a \in A_i} \frac{t_a}{c_i \sum_{j \in R} \delta_{a,j}} \quad \forall i \in R \quad (3.11)$$

where: a = Link with index a
 A_i = Set of links in route i
 t_a = Cost of link a ; distance in [km]
 c_i = Total cost of path i ; distance in [km]
 $\delta_{a,k}$ = Link-path binary that is one if link a is on route j and 0 otherwise

The Path Size Logit method is a good method to account for the interdependence between alternatives. In essence, the method penalises routes that have links in common with other routes. This approach can however also raise a problem. Duncan et al. (2020) describe this key issue of PSL as: "Unrealistic routes negatively impact the choice probabilities of realistic routes when links are shared." This issue is expected to be quite insignificant since the three generated paths, based on minimising an attribute type or disutility, are all beneficial for the utility function in their own way, thus never leading to completely unrealistic paths. Nevertheless, subsection 4.6.3 does reflect on this potential issue.

3.3. Saturation Analysis for HSR-stations

The second main methodological step of this thesis is a saturation analysis. Literature research did not provide a directly applicable method for estimating railway station saturation levels for platform tracks. However, the Institute of Transportation and Development Policy maintains an online open Bus Rapid Transit guide that contains a bus station saturation analysis approach (Institute for Transportation and Development Policy (ITDP), 2023). This approach was roughly adopted for this research and components were changed to fit the case of long-distance railway transport. The main concepts of saturation, capacity and demand do however remain. A benefit of this approach is that it also discusses the impacts of overrunning not only the theoretical capacity, but also the commercial capacity, which will be further elaborated on in chapter 5.

Institute for Transportation and Development Policy (ITDP) (2023) defines the saturation level of a BRT

station as the proportion of time that a docking bay is occupied. Application of this definition on the railway context changes the definition to the following; the saturation level of a railway station refers to the proportion of time that the platform tracks are occupied. A platform track is defined in this research as one of the designated tracks in a railway station where trains will stop and align themselves to the platform for passenger boarding and disembarking. The number of trains that demand to entry/exit are, partially, based on the passenger volumes generated with the transport model section 3.2.

The saturation level of a station is defined as the satisfied demand relative to the capacity for processing trains per day. This is presented in Equation 3.12. If this ratio is more than 1, the capacity is fully saturated. The set of evaluated stations, being centrally-located HSR-stations, is defined as S .

$$\text{Saturation}_s = \frac{\text{Train_Demand}_s}{\text{Cap_Station}_s} \quad \forall s \in S \quad (3.12)$$

where: Saturation_s = Saturation rate of station s
 Train_Demand_s = Daily traffic demand of trains that want to enter/exit station s
 Cap_Station_s = Daily traffic capacity of station s to process trains

The train capacity of a station is defined in Equation 3.13. The platform track capacity in this formula is dependent on the typology of a station, which refers in this research to a station being either a terminus station or through station. See section 1.7 for this definition and others.

$$\text{Cap_Station}_s = \text{N_Plat_Track}_s \times \text{Cap_Plat_Track}_s \quad \forall s \in S \quad (3.13)$$

where: N_Plat_Track_s = The number of platform tracks at station s
 Cap_Plat_Track_s = Platform track capacity per day of station s

The total train demand per day is defined as the sum of all long-distance trains and all commuter trains, which is mathematically defined in Equation 3.14. The passenger flows obtained through the transport model, described in section 3.2, are used as a proxy to calculate the LD_Demand_s . The Com_Demand_s is based on public data sources which are extrapolated to the prediction year of 2050. Chapter 5 describes in detail how this data was gathered and applied.

$$\text{Train_Demand}_s = \text{LD_Demand}_s + \text{Com_Demand}_s \quad \forall s \in S \quad (3.14)$$

where: LD_Demand_s = Daily traffic demand of long-distance trains at station s
 Com_Demand_s = Daily traffic demand of commuter trains at station s

The final equation in this methodological section concerns the calculation of the long-distance train demand, which provides as input for Equation 3.14. Equation 3.15 divides the throughput of long-distance passengers by the passenger capacity per train. It assumes that seating capacity equals the capacity of a train. This is assumed since it is common that you get assigned a seat on long-distance trains, unlike with commuting trains where you can also stand.

$$\text{LD_Demand}_s = \frac{\text{LD_Pax}_s}{\text{Seat_Cap} \times \text{Occ_Rate}} \quad \forall s \in S \quad (3.15)$$

where: LD_Pax_s = Sum of traversing and OD long-distance passengers per day at station s
 Seat_Cap = The (seating) capacity of passengers per train
 Occ_Rate = The occupancy rate per train

3.4. Logsum-based Consumer Surplus for Passenger Welfare

The objective of this research has been defined as the quantification of passenger welfare effects of re-locating HSR-services to dedicated train stations in the city outskirts. The most fitting procedure for this quantification is the use of the Logsum method in combination with RUM theory (Ben-Akiva, 1985). The Logsum is a commonly used method, both in- and outside academia, for doing an economic appraisal of transport policies or land use strategies. Logsum offers a precise formula for evaluating accessibility, grounded in the principles of discrete choice theory (Ben-Akiva, 1985) and the theories of neo-classical consumer surplus (McFadden, 1972). If assumed that utility increases linearly with income, the accessibility benefits can be easily translated to monetary terms by dividing it with the marginal utility of income,

i.e. the negative of the estimated cost coefficient. This provides the Logsum-based consumer surplus in monetary units, or in other words: the welfare gain in monetary units. This is why this method is well suited for doing an economic appraisal of a policy change, like for example relocating HSR-services. As described in section 3.2, the systematic-utilities of the RUM choice model are necessary as input. This is mathematically presented in Equation 3.16.

Although there are many benefits of the logsum-based approach, many institutions calculate the consumer surplus of infrastructure changes through an alternative method. An example of this is the "Guide to Cost-Benefit Analysis of Investment Projects for Cohesion Policy 2014-2020" by European Commission (2014). This alternative method is referred to in different ways across literature, but is usually referred to as either the Value of Time approach or Willingness to Pay approach. This approach remains very popular, although science has stated that the Logsum approach has 'theoretical advantages over more ad hoc accessibility-measures' Chorus and de Jong (2011).

In short, the logsum-based approach was selected as a method since it provides a comprehensive and automatic measurement of welfare effects. Unlike the WtP/VoT approach, which requires applying the rule-of-half to estimate benefits for travelers switching to improved alternatives. The logsum method inherently handles such complexities. Additional benefits of the logsum are that it can measure the welfare effects of joint changes in multiple attributes of many alternatives and that it can capture the effects of introducing or removing options from the choice set. This capability ensures a more accurate and theoretically robust assessment of consumer surplus and welfare changes, making it particularly suitable for evaluating infrastructural changes like relocating HSR services. Since the Logsum provides a closed form expression it is also computationally straightforward after application of RUM in the transport model Chorus and de Jong (2011).

An advantage of the Logsum method is at the same time its disadvantage. This disadvantage is the Logsum's aggregation of welfare effects, due to an infrastructure change, into a single monetary measure. While the comprehensive and automatic nature of the logsum method has previously been described as an advantage, it can be a drawback when detailed insights are needed for interpretation. The VoT/WtP approach, by contrast, requires separate calculation of welfare effects for different groups of passengers, providing more granular insights. This lack of fragmentation in the Logsum method can make it challenging to understand the distribution of welfare gains or losses among different passenger groups. It is however crucial to point out that the described transparency of the conventional VoT/WtP approach is only true in simple network situations, and decreases as the network increases in size and complexity (Jong et al., n.d.). Since the geographical scope of this research is an extensive long-distance network, the transparency argument does not hold water for this context. In addition, the VoT/WtP method is more labour intensive than the logsum method. In conclusion: the logsum method is selected for its theoretical advantages, comprehensiveness, allowance of multiple attribute change over multiple alternatives, and its computationally straightforward applicance.

Equation 3.16 shows how two logsums are computed and compared. The logsum is defined as the expected utility of a choice. Subtracting the logsum of a new scenario ($t=1$) by the logsum of the null-alternative ($t=0$) can therefore proof whether a welfare gain or loss has occurred in the (hypothetical) time period in between. The consumer surplus ΔCS is ultimately acquired when the subtraction, between squared brackets in Equation 3.16, is divided by the marginal utility of income. The marginal utility of income is measured in utils/€. Effectively, this provides you with welfare change in monetary units.

This study makes a logsum comparison between the relocated HSR-station alternative ($t=1$) and the original situation which has the HSR-station located centrally ($t=0$). The value used for γ is assumed to be the negative of the travel cost taste parameter β_{TC} .

$$\Delta CS = \frac{1}{\gamma} \left[\ln \left(\sum_{j=1}^J \exp(V_j^{t=1}) \right) - \ln \left(\sum_{j=1}^J \exp(V_j^{t=0}) \right) \right] \quad (3.16)$$

where: ΔCS = Consumer surplus i.e. passenger welfare effect in [€]
 γ = Marginal utility of income; i.e. $-\beta_{TC}$ in [utils/€]

The systematic utilities in Equation 3.16 represent the utilities over all modes J that belong to the same OD-pair for both scenarios. These are then used to calculate the expected decision utility of an individual that travels between those two cities, for both the $t=1$ and $t=0$ scenario. The output of the equation is therefore the consumer surplus that a long-distance traveller is expected to experience due to an infrastructure change when travelling from that specific origin (O) to that specific destination (D). To calculate the total passenger welfare effects of an HSR-service relocation, one should multiply the ΔCS per OD-pair with the number of passengers on that OD-pair. This total passenger welfare effect will henceforth be referred to as the summed consumer surplus, or mathematically as $\sum CS$.

There are multiple changes that will or may occur when relocating HSR-services from a city center to city outskirts location that impact the systematic utility, and thus the welfare gain. These are listed below for clarification reasons:

1. The access/egress time relocated HSR-station will increase.
2. The in-vehicle time and travel costs of passengers traversing the city may increase or decrease.
3. The access/egress time to an airport may decrease in the scenario that HSR-services are moved to that location.

As previously mentioned, a large benefit of the logsum method is that it can measure welfare effects of joint changes in multiple attributes of multiple alternatives, making it possible to take all of the above causes into account. Necessary inputs for this process are changes of passenger inflow, outflow and through-flow at HSR-station level, leading to the systematic utility changes that are necessary for Equation 3.16. The total change in systematic utility can be both positive and negative, resulting in either a welfare gain or loss. This implies a trade-off between passenger utility gains and losses.

The monetary value of ΔCS represents the future welfare losses or benefits in €, as calculated for the prediction year of 2050. If the long-distance passenger demand is assumed to be generated in one year time in 2050, then the ΔCS is the monetary welfare gain or loss generated by the HSR-service relocation in the entire year of 2050. An extra methodological step is performed to correctly value and interpret this welfare change for the base year of 2024. The method that was used for this step is the Net Present Value (NPV) method (Žižlavský, 2014; European Commission, 2014).

The NPV method is a widely utilised economic evaluation technique. It entails discounting all future cash flows—both inflows and outflows—associated with a policy change using a predetermined discount rate. The resulting discounted cash flows are then aggregated to determine the overall value of the strategy (Žižlavský, 2014). The method is often used in social-cost benefit analyses (SCBAs) to correctly value future costs and benefits to determine the expected social value of a project (European Commission, 2014; Widmer and Hidber, 2000). The classic notation of the NPV method is presented in Equation 3.17. The NPV formula that was applied in the execution of this study is visualised in Equation 3.18. The main difference with the classic notation is that it takes only the net cash flow of welfare change into account, corresponding with the defined scope of this research.

$$NPV = \sum_{t=0}^n \frac{NCF_t}{(1+r)^t} \quad (3.17)$$

where: NPV = Net Present Value [€]
 NCF_t = Net Cash Flow generated in year t as result of policy change [€]
 r = Discount rate [

$$NPV = \frac{\sum CS}{(1+r)^t} \quad (3.18)$$

4

Long-Distance Travel in Europe 2050

This chapter contains the entire transport modelling process in the context of long-distance travel in Europe 2050, from node selection and network construction to link flows and validation. The first three subsections describe how the necessary input for applying the combined mode route choice transport model was obtained and what choices preceded it. Subsection 4.1 presents how the urban nodes in the long-distance network were selected and defined. Then, attributes are collected for the three different modes in section 4.2. This is done primarily through acquisition from the literature for air and road transport. However, for rail, most of the information was obtained through the construction of the network in QGIS (2023) and analysis in Python Software Foundation (2024). Subsection 4.3.3 details how the choice parameters for the RUM model were estimated on reference studies and a Value of Time estimation. Section 4.4 presents the results of the various steps of the transport model, which were validated using relevant sources, as detailed in section 4.5. It is important to note that the verb 'validated' is used somewhat loosely, as the results from comparable transport studies do not represent the ground truth. However, 'validation' is employed in the title of this subsection due to the absence of a more fitting term. Lastly, this section describes the limitations of the transport model approach.

4.1. Origins and Destinations

4.1.1. Selection of Urban Nodes

In Europe, the focus of HSR services is primarily to connect first-tier, i.e. large, cities (Moyano and Dobruszkes, 2017; Hermelin and Gustafsson, 2022). The transport model described in this chapter therefore includes 124 of the most relevant cities spread across the entire geographical scope of section 1.7. It is visually presented in Figure 4.1. This selection is not arbitrary. Multiple studies have used this data set or slight variations thereof. The origin of this selection is the previously discussed publication by Donners (2016). This research defined a selection of the most significant metropolitan areas for a high-level European Network by first filtering larger urban areas connected by rail infrastructure, resulting in a long-list of possible cities. Then, these were classified according to population, regional GDP and research activities, which ultimately reduced the selection to a smaller subset of 110 cities. Further refinement involved eliminating or merging cities that were in too close proximity and essentially had overlapping catchment areas. Other refinement steps included the addition of capitals for under-represented countries and the addition of 14 non-Schengen cities. These 14 urban nodes are located in what are defined as "neighbouring countries" in the geographical scope of section 1.7.

There is only one mismatch between the geographical scope of this study and that of Donners, being Dublin. Ireland is excluded from this research, as previously discussed in section 1.7. The exclusion of Dublin sets the total number of cities in the set at 124, matching one-to-one the selection in the research by Grolle et al. (2024). The incorporation of this specific OD-set in this study assists in multiple steps of data acquisition in this chapter.

Another reason for selecting this specific set is its size. A more recent study than Grolle et al. (2024) and Donners (2016) is available, including public datasets, but it contains substantially fewer nodes

with 75 cities (Tanner, 2023). Since realism increases with the number of nodes, it was decided to apply the 124 of Grolle et al. (2024) and not the 75 of Tanner (2023). The downside of a network model with a larger OD-set is that it unavoidably leads to increased computation times.



Figure 4.1: The urban node selection. Created with QGIS (QGIS, 2023).

Before moving on to the definition of urban nodes, it is important to note that not every urban node in this thesis represents a single city. Donners (2016) included the assumption in his selection that closely located cities act in reality as single urban zones. This assumption was based on common practice in the airline industry. An example of this practice is the Rotterdam-The Hague airport, which serves the entire zone of the two cities. If nodes in the network have been merged like this, they are specified with the name of the largest city, in this case Rotterdam.

4.1.2. Definition of Urban Nodes

The "Urban Node" definition from TEN-T is officially part of the regulation and is of significant importance for the policies related to the TEN-T project (European Commission, 2021b). However, no clear definition or interpretation is provided in the content of the regulation, making it unclear what constitutes an urban node or how it is determined. That is why this thesis extracts its definition of an urban node from an additional source.

In this thesis, the concept of Functional Urban Area (FUA) is used to define the 124 urban nodes and their respective catchment areas for long-distance travel. According to the OECD definition, the FUA consists of 'the inhabitants of the city and the surrounding areas (commuting zone) where the labour market is highly integrated with the city' (OECD, 2023). This inclusion of the larger commute area is expected to provide relatively realistic sets of access/egress times. The FUA is one of the key definitions of this thesis and has therefore also been mentioned in the Table of Key Definitions in section 1.7. The visual representation of the Functional Urban Areas for the urban node selection is

provided in Figure 4.2.

The FUA concept was compared with alternatives from Eurostat (2020a). Examples of these alternatives were cities delineated by local administrative units (LAU) or metropolitan regions according to the NUTS3 classification (Eurostat, 2021). The following reasons were significant in selecting the FUA over the other alternatives:

- The geographical scope of this research is larger than the European Union, meaning that both NUTS3 and LAU are not applicable to the entire scope. This scope of Continental Europe calls for an approach similar to the FUA, which is jointly developed by the European Union and the OECD. The purpose of this collaboration was to create a harmonised global definition of cities and their areas of influence.
- NUTS3 regions were deemed too varying in size and inconsistent with the population size of cities. Often including entire agglomerations (as in Marseille) or just the city centre (as in Paris and London), and sometimes including vast rural areas around cities, distorting the access/egress distances for those cities.
- The LAU concept was deemed too narrow for this research. Inadequately representing the larger catchment area, but also too narrow for the scope of this research. This thesis concerns the relocation of HSR-stations to the city outskirts, but the LAU often do not include the more peripheral areas around a city.

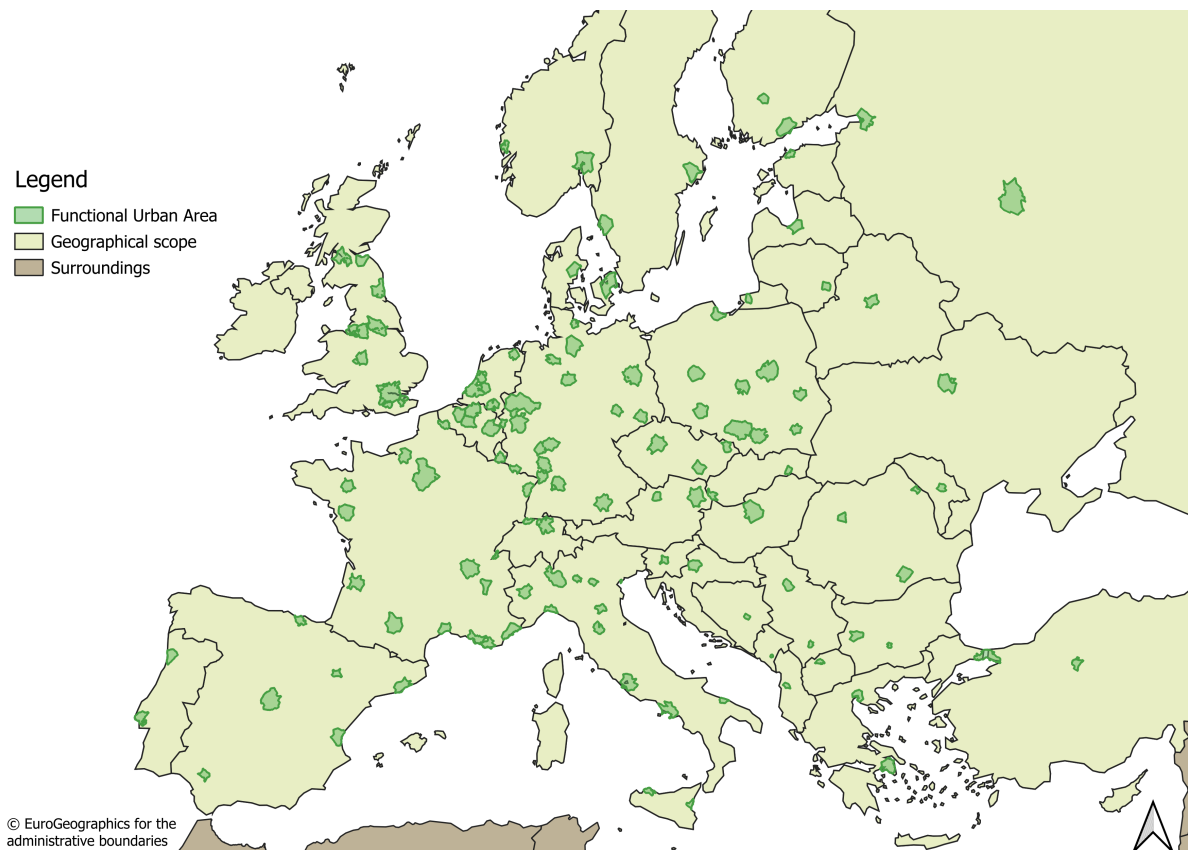


Figure 4.2: The Functional Urban Areas of the urban node selection. Based on (OECD, 2023) and created with QGIS (QGIS, 2023).

Although every definition of a city's catchment area simplifies reality, the FUA aligns well with theoretical expectations. Marti-Henneberg (2015) notes that the catchment areas for High-Speed Rail (HSR) stations typically span 25-30 kilometres. Importation of the 124 relevant FUAs in QGIS (2023) confirmed

that the definition of FUA aligns with the range of Marti-Henneberg, as many FUAs cover the city core and its commuting zone within the established radius of 25-30 km (Schiavina et al., 2019).

The cases in which Donners (2016) defined the main areas of the city as a single area, or urban node, align with the selection of the FUA as urban node definition. Two examples of these merges are Rotterdam-The Hague and the cities in the Ruhrgebiet in Germany (i.e. Essen, Duisburg, and Dortmund). Visual analysis of imported FUAs in QGIS (2023) confirmed that the OECD (2023) has merged the same city cores in the creation of the FUA concept as Donners (2016) has.

Finally, the adoption of the FUA concept for defining urban nodes is becoming more common, with Bruno (2022) and Borgogno (2023) having adopted the FUA concept for largely the same reasons. The use of FUA as a commuting zone for an urban node is used not only in scientific research, but also in the advisory report of EY (2023) to Europe's Rail Joint Undertaking (ERJU).

4.2. Attributes of Transport Networks

4.2.1. Rail Network

Edge Selection and Characteristics

Acquiring geographical data was the initial and most crucial step to enable the execution of this transport model. The aim was to create a geographical network with QGIS data that could then be loaded into Python to execute the methodological steps of the Combined Mode-Route Choice Transport Model (QGIS, 2023) (Python Software Foundation, 2024). Fortunately, a shapefile containing such data was openly available online.

Geographic data from a previous version of the TEN-T policy, originating from 2017, was extracted from an online open source (European Union Agency for Railways, 2022). The shapefile did not contain railways for the entire geographic scope, but it did for the Member States. The shapefile was therefore altered to contain the entire geographical scope, in accordance with the maps in the appendix of the TEN-T regulation (European Commission, 2021b). When constructing edges for neighbouring countries, only the necessary edges were included to service the selected set of 124 cities, with a preference for high-speed lines. Since the TEN-T policy excludes the UK from the list of neighbouring countries, the edges on the island of Great Britain are based on a previous version of the TEN-T regulation from before Brexit (European Commission, 2013). The railway network was constructed in QGIS with EPSG: 3035 Coordinate Reference System (CRS), which is designed specifically for Europe and uses a projected coordinate system. A reason for adopting this CRS was that many EU data sources use this CRS (Eurostat, 2021). All Figures in this thesis that are retrieved from QGIS were created in this CRS.

The goal of this phase was to store multiple attributes per edge that are necessary for the transport model. The way in which these were generated is elaborated in this section. The following were identified as essential for this thesis:

1. Distance: The length of the edge in [km];
2. Type: Defined as either 'Conventional' rail or 'High-speed' rail;
3. Speed: The average speed at that type of rail, provided in [km/h] and generated based on 'Type';
4. Status: Representing the construction status as "New Construction" or "Existing" according to Figure A.1. Applied for forecasting induced demand volumes;
5. Area: This attribute can contain a city name that corresponds to an urban node or be empty. The edge is located in the FUA of a node if it contains the corresponding name of that node.

A large number of actions were performed in the QGIS file to make it processable and efficient for Python computations. These actions include:

- Drawing missing links according to European Commission (2021b) for all countries except the UK, for which European Commission (2013) is used. The relevant appendix maps were loaded into QGIS and used as an overlay upon which the edges were manually constructed and the necessary details were applied. In addition, OpenStreetMap was used because it is possible to

load it into QGIS as a layer (OpenStreetMap, 2024), making it easy to draw existing lines on the basis of that map. For each line that was drawn, the rail type was manually entered, being either 'Conventional' or 'High-speed'.

- Cutting edges at crossings to make the network navigable, so that it is possible to travel from one edge to another when generating the shortest paths.
- Removing edges that are dead end and do not contribute to reaching stations, as selected in the next section. This step was performed to reduce the number of edges and therefore reduce the computation times. Dead-end paths do exist in the network in the case of terminus stations.
- Removing edges that are visually unlikely to be chosen in this model. Section subsection 3.2.3 discussed that the shortest paths were generated according to a labelling approach based on time, distance, and disutility (with the latter being inherently based on the time and distance attribute). Therefore, if two edges exist between two endpoints and one is both shorter and high-speed while the other is longer and conventional, the latter is deleted since it will never be chosen. This approach was not all-embracing; only edges that were visually evident to never be chosen were removed. In many cases, this involved edges that went through cities that were not in the dataset. This edit has led to faster processing times for path generation, as it reduced the number of edges.
- Drawing transfer edges between terminus stations in cities where transfer is not possible through the rail network. This specifically concerns London, Budapest, and Paris. The model includes, respectively, 3, 6, and 3 terminus stations in the city centres of these cities, between which it is not possible to transfer or travel by train. Therefore, lines were constructed between these inner-city stations in this rail network, typed as 'Virtual Transfer' for the attribute 'Type'. Besides this, they have a speed equal to the average access/egress speed for centrally-located stations, which is 19 km/h, as will be elaborated on later in this section. This approach was only performed for these three cities; other cities with multiple stations have their stations connected by rail, as will be discussed in the next section.

After performing the above series of actions to make the data file usable, several steps were taken to assign realistic attributes per edge, such as the distance, speed, status, and area mentioned above. Estimation of the distance was straightforward. In QGIS, SQL code can be applied which automatically generates the distance in kilometres of each edge. The margin of error when applying this function in QGIS is 1 metre (EPSG.io, 2024).

The next step to generate attribute data was the quantification of average speeds for both the "conventional" and "high-speed" edges, which are the types of railway defined in European Commission (2021b) and therefore used in this transport model. European Commission (2021b) does not quantify an average speed, but defines high speed as being able to reach speeds of 200 km/h. An additional difficulty arises due to the fact that the 124 cities in the dataset are not the only cities that will be visited by trains operating between them. Other research indicates how much time deceleration, acceleration and dwelling times per station take (Grolle et al., 2024), but it is unknown how many stations are present along each line. Not knowing how many stops exist along a line makes it infeasible to estimate rail travel times by using these station-to-station speed profiles. That is why a different approach was executed that estimates average speeds for conventional and high-speed rail edges, while assuming on the basis of real-world scenarios that once in a while the train stops at a station that is not within the dataset. This is especially important for conventional train speeds, since conventional trains tend to stop more often and at cities smaller in size than the selected 124 in this research.

An expert from Royal Haskoning DHV, with the professional title 'Consultant Rail' and more than a decade of experience in that department, was consulted to estimate the speeds for both types of edges. The expert's advice was to select a number of currently existing edges that are relatively new and use modern technology and retrieve average speeds inclusive stops from that data. The selection provided was ensured to satisfy these characteristics. Most of them are also present in the TEN-T policy of 2050 (European Commission, 2021b). The trips and corresponding times were acquired from the Deutsche Bahn route planner (Deutsche Bahn, 2024b). They are presented in Table 4.1 and Table 4.2. Using Google Maps, the distance travelled by rail along the line was determined, leading to an average operating speed per trip including stops (Google Inc., 2024). These speeds were then averaged to mean operating speeds of approximately 215 km/h for HSR and 130 km/h for conventional rail. In conclusion,

the resulting values include stops that might not be present in this model and are therefore more realistic than only assuming slower speeds around the stations in the selected 124 cities. The assumed average speed was also considered realistic since PTV Group (2023), a German consulting company with expertise in rail mobility, assumes an average speed of 210 km/h, including stops, for high-speed trains.

Lastly, analysis of the results illustrated that the average number of stations per distance is approximately 1 per 466 km for high-speed rail, while for conventional rail it is 1 per 169 km. This is in line with what was previously expected, namely that conventional trains tend to stop more often. It is illustrated by the last entry of Table 4.2 that the stops of conventional trains include urban areas which were excluded in the selection of this thesis, since Göteborg and Stockholm are the only two cities in Sweden in this thesis, while the table shows that the service between them includes two other cities. Therefore, this approach based on average operating speeds is in fact a better fit for this thesis than applying acceleration, dwelling, and deceleration times per station for only the selected set of 124 urban nodes would have been. This would have led to an underestimation of total travel times by conventional trains and therefore to an overestimation on those railway edges.

Table 4.1: High-speed train travel data as retrieved from Deutsche Bahn (2024b).

Origin	Destination	Time [min]	Dist [km]	Speed [km/h]	#Stops
Paris Gare de Lyon	Marseille St Charles	185	740	240	0
Munchen Hbf	Berlin Hbf	226	660	175.2	2
Barcelona Sants	Madrid Atocha	150	620	248	0
Milano Centrale	Roma Termini	180	570	190	1

Table 4.2: Conventional train travel data as retrieved from Deutsche Bahn (2024b).

Origin	Destination	Time [min]	Dist [km]	Speed [km/h]	#Stops
Paris Austerlitz	Orleans	60	125	125	1
Koln Hbf	Hambrg Hbf	225	430	114.7	0
London Kings Cross	Edinburgh	260	625	144.2	4
Wenen	Salzburg	145	310	128.2	3
Göteborg Central	Stockholm Central	182	450	148.4	2

The speeds of 130 km/h and 215 km/h were respectively applied by using the 'high-speed' and 'conventional' entries of the edge attribute 'type'. There was, however, one more step concerning operating speeds that had to be taken to accurately model the hypothesised passenger welfare effects around cities; namely the distinction between speeds of high-speed trains in peripheral areas versus urban centres.

Visual analysis of OpenRailwayMap illustrated that high-speed trains on average decrease their speed in urban areas (Matheisen et al., 2024). According to the rail expert mentioned above, this is not for noise or emission reasons, but more because the urban rail infrastructure is often shared by multiple types of trains and is therefore unsuited to provide high-speed operations. OpenRailwayMap illustrates this, showing that urban sections of railway infrastructure are often shared between high-speed train lines and conventional train lines (Matheisen et al., 2024). Analysis through OpenRailwayMap showed that in many cases, the urban speeds of both high-speed train lines and conventional train lines do on average not exceed 130 km/h in densely built areas. Since this matches precisely the defined average operating speed of conventional trains, all edges that are located in urban city cores were reassigned to be 'conventional' rail.

The definition of urban city core in this thesis is that of the OECD and the European Commission in (OECD, 2023). This source has previously been discussed in section 4.1, where it concerned the definition of the Functional Urban Area (FUA). However, this source does not only contain geographic data of the FUA concept, which are assumed to be the commuting zones of cities, but also contains 'urban centres'. These urban centres from the GHS (Global Human Settlement) dataset are 'defined by specific cut-off values on resident population and built-up surface share in a 1x1 km uniform global

grid'. OECD (2023) applies the same definition for 'central areas' as was defined in section 1.7 so it is consistent with the rest of this research.

Importing these GHS urban centres from OECD (2023) into QGIS illustrated that these urban centres align relatively well with the range of densely populated areas, in which modern high-speed trains decrease their speeds to on average 130 km/h. The next step to implement the described approach, and to decrease all edge speeds in the GHS urban centres to that of convention rail (130 km/h), was to cut all edges in the shapefile at the borders of the urban centres. All edges that are located within the GHS urban centre were then assigned the type 'conventional' and the corresponding speed of 130 km/h.

Two pairs of examples are provided in Figure 4.3 and Figure 4.4. With on the left side the current situation according to OpenRailwayMap (Matheisen et al., 2024) and on the right side an export of the final situation in QGIS. The QGIS export contains conventional speeds in the urban centre and high-speed edges outside of the urban centre.

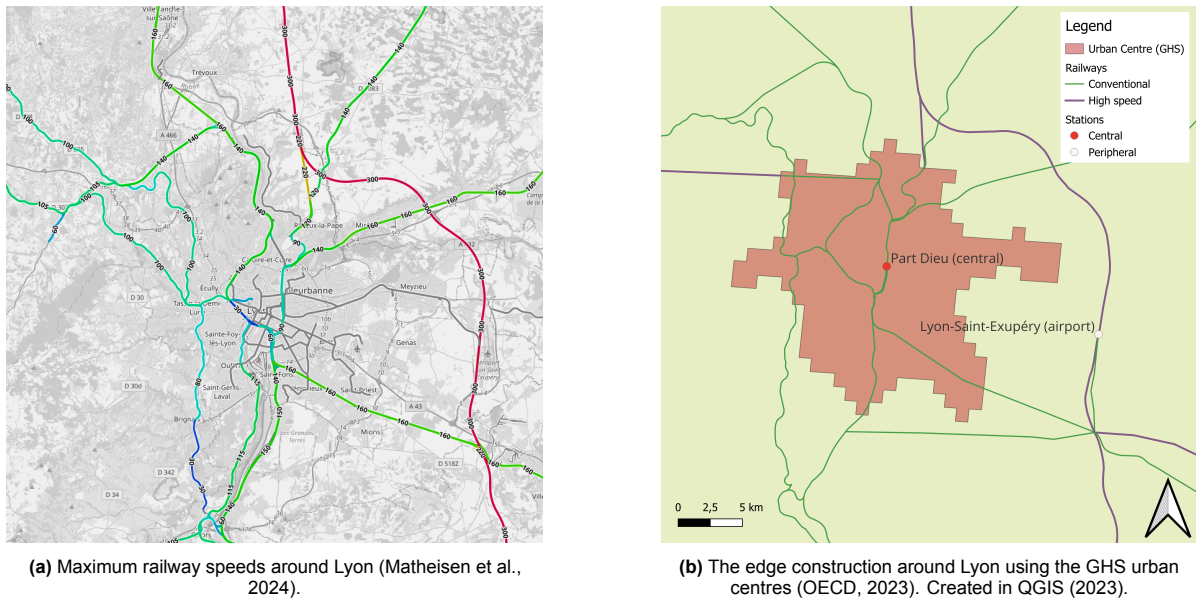


Figure 4.3: Comparison of the maximum railway speeds distribution of OpenRailwayMap (Matheisen et al., 2024) with the assumed urban and peripheral operating speeds in QGIS (2023) for Lyon.

The fourth edge attribute that had to be defined was the construction status attribute. This data was already largely present in the initial shapefile of DG Mobility and Transport of the European Commission (2024). The data from this initial shapefile was updated with information from the TEN-T policy (European Commission, 2021b). The result is presented in subsection 4.4.4, where the construction status is applied in the generation of induced demand.

For assigning the fifth and final edge attribute 'Area', the dataset of (OECD, 2023) was used once again, only this time using the FUA commuting zones. All edges were cut at the FUA borders of the 124 urban nodes. Subsequently, all edges that were located within the functional urban areas were selected. After selection, these edges were assigned the name of the FUA, completing this final step. The edges that are not within an urban area, i.e. commuting zone, do not have an entry for this attribute.

After preparing the edges in the QGIS shapefile, several checks were performed. Many of the existing edges were verified with OpenStreetMap (OpenStreetMap, 2024). A smaller number of existing edges, randomly selected per country, were verified with OpenRailwayMap (Matheisen et al., 2024). Lastly, an interactive online TEN-T map was used to check a large number of edges (DG Mobility and Transport of the European Commission, 2024).

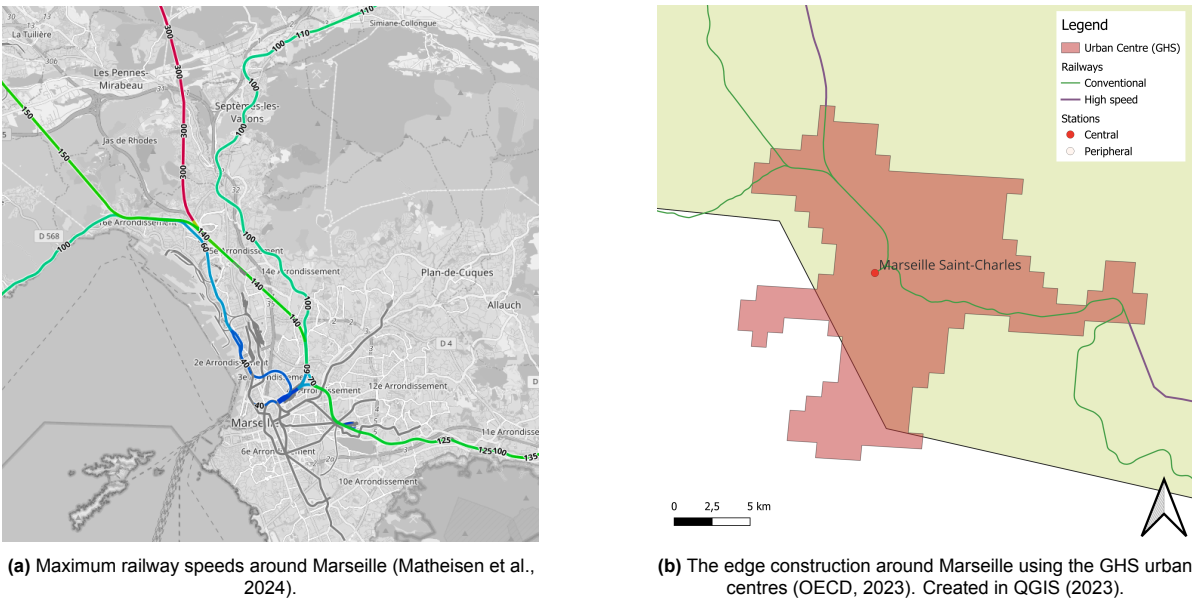


Figure 4.4: Comparison of the maximum railway speeds distribution of OpenRailwayMap (Matheisen et al., 2024) with the assumed urban and peripheral operating speeds in QGIS (2023) for Marseille.

The definitive network contains 3661 edges and is visualised in Figure 4.5.



Figure 4.5: The comprehensive TEN-T network and rail in neighbouring countries. Verified with European Commission (2021b) and created with QGIS (2023).

Station Selection and Characteristics

This subsection describes how the stations were selected for research and which data is included in every node. Common to the assigned data per edge, data is also stored per node. The necessary data contained in every station node is the following:

1. ID: An integer ranging from 1 to 154.
2. Area: The name of the urban node (FUA) in which the station is located.
3. Name: The name of the station.
4. Centrality: Either 'Peripheral', 'Urban' or 'Central' in accordance to the definitions in the key definitions list in section 1.7;
5. Access/egress distance: The weighted access/egress distance based on the population distribution in the commuting zone (FUA) in [km];
6. Access/egress speed: The average access/egress speed to/from the station, dependent on the type of centrality in [km/h];
7. Access/egress time: Calculated by dividing the two attributes above [h].
8. HSR-services: A binary that represents whether a station provides HSR-services (1 = True);
9. Terminus station: A binary that represents whether a station is a terminus station (1 = True);
10. #Platforms: The number of platforms that might be used for long-distance travel.

The first four attributes are self-explanatory with the previously defined concepts. The attributes labelled 5 to 7 are discussed in the next subsection. Attributes 8 and higher are discussed in chapter 5.

The remainder of this subsection discusses the comprehensive selection of stations, an element that is vital to this research. The selection process of the station nodes is split into two systematic approaches with two different sets of criteria, one set for urban stations (U) and one for peripheral stations (P). The selection rules are labelled with the Roman numeric system, with I to V being rules for urban node selection, and VI and VII being rules for peripheral node selection.

The goal of the urban station criteria was to create a set of stations that could realistically connect the 124 urban city areas with each other, while being located along the edges of the Comprehensive TEN-T. Realistic in this context means that there is a decent chance that the selected stations will serve long-distance trains in 2050. The selection criteria do not only aim to satisfy the defined goal, but also to limit the size of the station set for scoping and computational reasons. For this reason, principally one station is selected per city. Therefore, it is assumed inherently that future long-distance trains will stop at those stations.

A comprehensive procedure was developed that selects stations for 124 cities, while preventing 124 manual researches to existing stations and urban development plans. This procedure for the base scenario assumes that urban stations will continue to exist in the locations where they are currently. The only railway station developments included in addition to the TEN-T policy are the selection of Amsterdam Zuid as the station for Amsterdam (Hermanides, 2018), the new Brno Main Station (Municipality of Brno, 2023) and the new pair of stations in Birmingham (BBC, 2018). These four station exceptions are referred to in the selection rule columns of the tables of Appendix B as E, for exception, and have previously been discussed in section 1.7 as the only three local policy additions to the TEN-T policy (European Commission, 2021b). The only other exception to the 'existing station' prerequisite is decision rule VII; that allows for the addition of a peripheral station if the envisioned TEN-T infrastructure strongly suggests that an airport will be connected to the TEN-T network through high-speed rail.

Two criteria were defined for the urban station selection procedure:

- U1 The station must be located along an edge of the Comprehensive TEN-T policy, serving conventional trains, high-speed trains, or both.
- U2 Urban stations are defined as those within areas with a population density greater than 300 people per square kilometre.

The applied selection procedure for urban stations is as follows:

- I If a selected city contains a station that is directly named after the city or a so-called 'Central Station', including non-English translations thereof like 'Hauptbahnhof' or 'Gare Centrale', only that station is included in the station set. An additional criterion is that the station name must contain the same name as that of the urban node (FUA). A station is also considered to be a 'Central Station' if the name literally translates to 'principal station' or 'main station'.
 - Argumentation: "Central Stations" are defined as the primary railway stations of a city and act as termini for a multitude of rail services - suburban, regional, domestic and international (Kellerman, 2012). Therefore, it is assumed that long-distance trains in the Comprehensive TEN-T make a stop at the Central Stations of the cities they visit, if the city contains one. This is in line with the finding of Albalade and Bel (2016) that most European HSR services originate and terminate at central stations.
- II If no station exists that is named "Central Station" or an equivalent thereof, the following approach is adopted: A station is selected as the single main city station if it is a long-distance terminus station which is centrally-located ($1500 > \text{pop}/\text{km}^2$), and if there are no other central terminus stations present in that city that serve long-distance traffic.
- III An exception to the "single station" rule of I and II occurs when the selected main station is a terminus station and there also exists a through station in the urban area. The through station must serve high-speed railway lines that travel past the city centre, and may not be located in the extended direction of the track from the terminus station.
 - Argumentation: Through stations that exist separately from a terminus type major or "Central" station, are usually built with the intention of increasing high-speed train throughput capacity. Both Rome and Lille are examples of this. There are, however, also examples of this outside of the station selection of this research, for example in The Hague in The Netherlands (Matheisen et al., 2024).
- IV If a selected city contains multiple main stations that serve distinct long-distance railways, and not one main station that could serve all long-distance railways, all of those major stations are included in the station set.
 - Argumentation: These major urban stations currently serve various long-distance trains, although they are located in the same city. Therefore, the inclusion of multiple stations is needed to provide rail passenger transport in every direction of the TEN-T network around the city. This selection rule applies, among others, to London.
- V If the city in question does not fit one of the previous selection rules: The main urban station is selected based on the number of platform tracks identified through OpenRailwayMap (Matheisen et al., 2024). The station, that is located along the TEN-T edges, with most tracks is selected. An additional constraint is that visual inspection of OpenRailwayMap must show that it serves all of the surrounding TEN-T edges, and thus long-distance railways. Confirmation of the selection as main station is done by performing a small desk research.

The results of this procedure are presented in Appendix B. A major assumption in this procedure is to select, in most cases, only one station per city. This does not impact the results much from a service perspective, since European long-distance trains commonly visit only the primary railway stations of a city (Kellerman, 2012). It does however impact the average access/egress time. Having multiple stations present in a city that all provide long-distance services will decrease the average access/egress time for such a long-distance trip, since people could choose the station which is closest to them. An example of this is Berlin Spandau, which is not included in this selection (Matheisen et al., 2024).

At the same time, having multiple HSR stations per city is considered ineffective in time and cost (European Court of Auditors, 2018b). The literature suggests that high-speed stations should have varying catchment areas, and this objective is not achieved when stopping multiple times in a city. This argument for efficiency is supported by the position of (Banister and Givoni, 2013). They make an argument for one stop per city, since every intermediate stop extends total travel time by an average of 4 to 12 minutes, and reduces the average speed by 3 to 16 km/h.

In conclusion of the urban station selection procedure; it is assumed that most cities have only one station. However, it should be acknowledged that this assumption generally increases the access and egress times and is not realistic in all situations, which is why rules III and IV allow for exceptions.

The selection of peripheral stations is based on the following two criteria:

- P1 The station must be located along an edge of the Comprehensive TEN-T policy, serving either high-speed trains or high-speed and conventional trains.
- P2 Urban stations are defined as those within areas with a population density of less than 300 people per square kilometre.

The selection procedure for the peripheral stations is provided below. The selection rules continue in the style of the Roman numerical system to create a coherent set.

- VI If a currently existing peripheral railway station within a city's Functional Urban Area (FUA) is or will be located along an HSR TEN-T edge, it is included in the station dataset.
 - The peripheral stations in today's Europe are mainly airport stations, with Frankfurt Flughafen Fernbahnhof and Brussel Zaventem Airport being examples. Exemptions on this trend are stations like Montpellier Sud-de-France and Paris Marne-La-Vallée-Chessy.
 - An example of an excluded airport station that is connected to the TEN-T rail network is Zurich airport. The reason for its exclusion is that it is not connected via HSR (European Commission, 2021b).
- VII An exemption to 'existing station' prerequisite is made if the Comprehensive TEN-T design clearly shows that an edge will be specifically constructed to connect an existing peripheral airport through high-speed rail.
 - The only applicance of this decision rule is the case of Riga International Airport. Desk research confirmed that this airport will indeed be connected to the TEN-T high-speed network (Baltica, 2023).

The total overview and allocation type are presented in Figure 4.6. The selection of many stations in western Europe were verified to be halts in current-day long-distance services through the use of a French TGV services map (TGV, 2020).

Access/Egress Times

The access/egress time approach for long-distance rail trips is crucial to the topic of this thesis, which concerns the relocation of stations from central areas to peripheral areas. This section discusses first how the access/egress distances were determined and then, split between urban stations and peripheral stations, how the speeds were determined.

The access/egress distances per station were derived using a population density grid in QGIS. The grid that was applied for this objective is the Geostat population density grid from 2018, which contains grid cells of 1 km² (Eurostat, 2020a). The applied catchment area for the population-weighted access/egress distance calculation was based on the FUA concept (OECD, 2023), which is assumed to be the city's commuting zone. Note that the distance calculation considers the current distribution of the population without accounting for trends in urban development such as growth and gentrification. An example of such a population grid is provided for Linz in Figure 4.7.

The process of defining the average access/egress distance in QGIS per station was executed for the entire station selection, and required the following steps:

1. Generate per station in an urban node's FUA the geodistances between the gridcells and the station.
2. Multiply the geodistances per gridcell with the population that resides within that squared kilometre, and save this variable per gridcell.
3. Sum all of the multiplied population-geodistance variables of that urban node, and divide this through the total population of the urban node, i.e. the population within the FUA. This provides the average access/egress distance.



Figure 4.6: Selection of railway stations in Europe, colour-coded based on centrality (Eurostat, 2020a). National borders are adapted from Eurostat (2020a) data. Created with QGIS (2023).

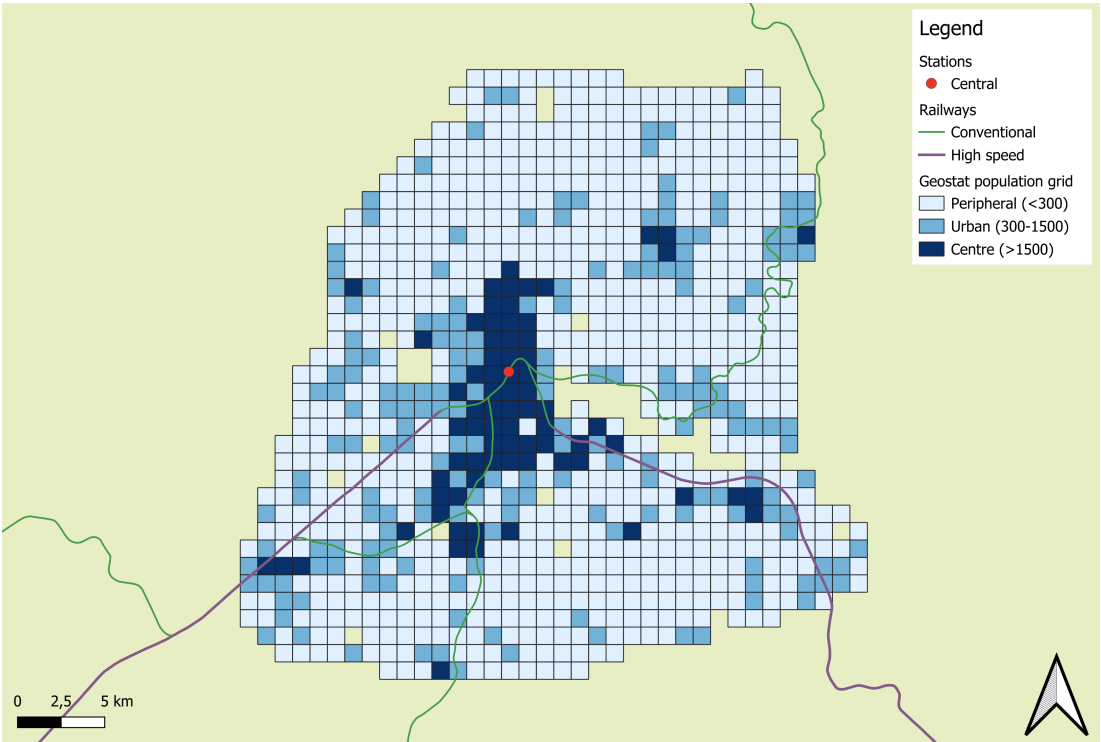


Figure 4.7: The population grid of Linz as used in the determination of the access/egress distance, bounded by the previously defined Functional Urban Area (Eurostat, 2020a; OECD, 2023). Created with QGIS (2023).

The procedure of generating access/egress times requires not only distances, but also speeds. That is why the remainder of this section focusses on the determination of access/egress speeds.

A first step in quantifying the access/egress speeds was defining which modes are used for access/egress in the urban and peripheral context. Literature was analysed for access/egress modes in the context of long-distance rail trips, but few sources could be found. Two of the sources that specifically discuss this subject are Moyano, Moya-Gómez, and Gutierrez (2018) and Martín et al. (2014). The first research, respectively, states that analyses on access/egress times to/from high-speed rail (HSR) stations are seldom specified in the literature, while the importance of stations' local accessibility and their integration into the urban transport network are influential determinants in the assessment of high-speed rail trips. The research by Martín et al. (2014) assumes that private car and public transport (PT) are the main modes of access/egress in long-distance HSR trips. It was concluded from desk research and this concise literature analysis, specifically from the conclusion of Moyano, Moya-Gómez, and Gutierrez (2018), that no recent Europe-wide access/egress mode choice data is available in the context of long-distance trips.

However, it is suggested that the main access/egress modes for long-distance rail trips are PT and cars. This is why it is assumed that cars and transit together form 95% of the mode share to urban stations for high-speed rail. This value also makes sense logically. It seems implausible that people will cross half of a large city like Berlin, containing 4 million inhabitants, by foot when initiating long-distance travel. Especially since people usually carry luggage when travelling long distance. However, much smaller cities with smaller distances, such as Podgorica and Groningen, are also present in the dataset, where more people might walk or cycle, even while carrying luggage. For this reason, it is assumed that the active modes are capped at 5%.

There may not be much data on access/egress modes in the long-distance rail context, but sufficient data is available on railway stations in general. Datasets from four varying EU countries were found after extensive literature review, albeit from a couple of decades ago for the Italian study. This data is presented in order of publication year in Table 4.3. The origin of the data is also provided, illustrating that the way of recording is similar for three out of four studies. Only the French data is an exception, being based on a household travel survey. This dataset does however contain many participants across France, which adds to the reliability of the results. Lastly, it is hypothesised that the active modes of Table 4.3 show a high modal share due to the fact that the data concerns conventional railway stations, including stations in relatively small towns and small intermediate stations in suburban areas, decreasing the average access/egress distance.

Table 4.3: Average access/egress mode choice percentages for conventional railway stations across four European countries. Based on respectively: 1. Crisalli and Gangemi (1997); 2. Gregor and Lep (2014); 3. Hasiak (2019); 4. Ton and Heuvel (2023)

	Country	Car	PT	Bike	Walk	Other	Data origin
1	Italy	29	34	9	27	1	Field survey on the Turin-Venice corridor
2	Slovenia	31	11	3	55	0	Field surveys at couple of stations
3	France	20	28	5	46	1	Household travel survey across France
4	The Netherlands	8	26	26	39	1	Field surveys at many Dutch stations
	<i>Average</i>	22	25	11	42	1	

Combining the average modal shares of Table 4.3 with the previously defined limit of at maximum 5% of active modes, generated the mode shares as presented in Table 4.4. This was done by extrapolating the 'Car' and 'PT' mode, in the ratio of Table 4.3, to 95%. The same procedure was applied to 'Bike' and 'Walk', but then to a combined total of 5%. The option 'Other' was excluded since it is infeasible to estimate speeds for and since it entails only 1%. In addition to mode shares, the detour and speed per travelled distance were also required to calculate the average speed per geodistance. The aim for generating a speed per geodistance arises from the fact that the access/egress distances were also determined as geodistances, i.e. distances 'as the crow flies'. Detours are included to represent that

there exist geographical barriers along a route, which vary per mode.

The required detours were estimated based on literature. The first entry of Table 4.4 was based on research of Lee et al. (2023), which states a detour index for car of on average 1.5, based on network models of various metropolitan cities around the world. The detour factors for PT and biking originate from the same research, which compares their detour factors after creating a network model for Vienna. The fourth detour factor is an estimation based on the previous three. In the literature, no detour factor for walking could be found, but it was assumed to be significantly lower than the other factors. The argument for this is that a walking individual is more flexible in his route choice, having the possibility to cross, for example, alleys, squares, and parks. This is why it was estimated at 1.15. The reliability of these results is limited, since only a few sources were found. The values that were found do, however, originate from cities that correspond to or are comparable to the cities in the urban node selection of this research.

The speeds were estimated in the same approach, through a review of literature. The average speed on the urban road is estimated to be 30 km/h, according to research on cars (Liao, Gil, Pereira, et al., 2020) and city buses (Leth, Shibayama, and Brezina, 2017). The speed of PT was estimated to be 27 km/h. This value was averaged from the research of Rothfeld et al. (2019), which estimates travel pattern data through the use of a Google Maps API (Application Programming Interface) for the access/egress of airports. Although this value originates from an airport context, it was applied here in the context of access/egress of long-distance rail trips. This was done due to a lack of data, but was deemed suitable since both originate from an urban context. The speeds of walking and cycling originate both from (Zhao et al., 2019), a research on last-mile travel mode choice that includes speed data from a field experiment.

After acquiring these four speeds, they were divided by the corresponding detour indices to calculate the geodistance speeds. The results are provided in Table 4.4. Geodistance in the table refers to the distance 'as the crow flies'.

Table 4.4: Access / egress details of urban stations.

Mode	Shares [%]	Detour	Speed (travelled distance)	Speed (geodistance)
Car	44	1.50	30	20
PT	51	1.40	27	19
Bike	1	1.30	11	9
Walk	4	1.15	5	4

Multiplication of the shares per mode with the corresponding geodistance speeds in Table 4.4, and then summing these, generated a weighted average geodistance speed. This average speed as the crow flies is 19 km/h for urban stations, i.e. stations that are located in a central or urban area. See section 1.7 for the definitions.

Scientific literature containing data on the access/egress trip characteristics for peripheral HSR-stations could not be found, but secondary sources that contain these could be found. The data site of the French rail operator SCNF (2017) contains a dataset that includes the modal split for access/egress modes per station in France. Three peripheral HSR-stations of the dataset, which are also included in the station selection of this research (see Appendix B), were used to estimate the average modal split. The conclusions are found in Table 4.5. The average modal split for the peripheral stations is very similar to the results of access/egress modal split for HSR-stations in China, which were identified in the literature analysis as 62% for road and 38% for PT (Yang et al., 2019). This similarity is not surprising, since most Chinese HSR-stations are also located in the periphery.

This research assumes that peripheral stations, including those that were generated in the experiments of chapter 6, must be well connected via PT transit. This is in line with the encouragements in Marti-Henneberg (2015) and Wenner and Thierstein (2022), which were both discussed in chapter 2. These publications state, respectively, that intermodality should be improved around railway stations, especially those in peripheral areas, and that HSR-stations should be well embedded in public transport

Table 4.5: Access/egress mode choice percentages for peripheral stations.

Mode	Marne-La-Vallée-Chessy	Lyon Saint Exupery	Aéroport Charles de Gaulle 2	Avg.
Road [%]	71	78	42	63
PT (rail) [%]	29	22	58	37

networks. Their advice was taken to heart by applying the data in Table 4.5, which represents three stations that are connected by metro or conventional train. Therefore, satisfying the assumption that HSR-stations are well connected through PT transit.

The Google Maps route planner was consulted to estimate access/egress speeds that fit these three peripheral stations. This approach automatically incorporates detours, as Google Maps takes geographical barriers and infrastructure into account. To incorporate the shifting urbanity into these speeds, the city centre was taken as a starting point. By doing so, it is ensured that the car speed includes traffic regulations and traffic intensities that belong to both the urban and peripheral environment, increasing the realism of the estimation. The results are presented in Table 4.6.

Table 4.6: Travel times and distances for the three French peripheral stations (Google Inc., 2024).

	Marne-La-Vallée-Chessy	Lyon Part Dieu	Aéroport Charles de Gaulle 2 TGV
Car TT [min]	45	32	55
PT TT [min]	55	40	52
Geodistance [km]	20	19	22

The average speed, as the crow flies, was defined to be 27 km/h for accessing and egressing peripheral stations from its corresponding commuting zone. This was done by combining the average modal share of Table 4.5 with the average speeds per mode calculated from Table 4.6. The consequence of taking the city centre as the starting point instead of taking a population-weighted gravity point as the starting point is discussed in subsection 4.6.3.

In-vehicle Travel Times

The first step to compute the in-vehicle travel times for the train was to generate the shortest routes. This process was carried out according to the labelling approach of Fiorenzo-Catalano, Van Nes, and Bovy (2004), which was previously discussed in chapter 3.

The routes were generated using a NetworkX function called `shortest_path()`. It allows for assigning an edge attribute as weight. Three different weights were assigned to three different generations, each resulting in a path that minimises its weight between the origin and destination stations. The selected weights, and corresponding approaches, are the following:

- 0 In-vehicle time: The corresponding edge attribute is 'in_veh_time' in hours. This edge attribute is quantified by using the 'distance' and 'speed' attributes per edge that was discussed earlier in this section.
- 1 Distance: The corresponding edge attribute is 'weight' in kilometres. Distance is included because travel costs, being one of the two attributes in the utility function, are assumed to scale directly with the distance travelled. This assumption will be further described later in this section.
- 2 Disutility: The corresponding edge attribute is 'disutility' in utils. This edge attribute is quantified by taking the negative of Equation 3.4 per edge.

Visual inspection of the initial shortest paths, which were saved as dictionaries, showed that they barely visit stations along their route. This is logical since many train stations in Europe are located in city centres and the fastest path usually does not pass through urban centres. Especially terminus stations were never visited on these initial shortest paths, since terminus stations require the use of the same network edge twice. This can never result in a shortest path, since every edge has a cost (either time, distance, or utility).

The observations in the last paragraph are in line with the hypothesis of this research, namely that urban rail routes are ineffective for many traversing passengers. However, the inclusion of stations along a shortest path was required for the implementation of the saturation analysis in chapter 5 and the analysis of passenger welfare effects in chapter 6.

Therefore, the shortest paths were ensured to visit at least one station per urban area through which they pass. This aligns with the procedure previously discussed in the station selection subsection, which included arguments from European Court of Auditors (2018b) asserting that stations should not have overlapping catchment areas. Given that in this thesis, the catchment areas are defined as the FUA per city, and some FUAs encompass multiple stations, it is reasonable to assume that the rail shortest paths need to visit only one station per city. This corresponds to the recommendations of Banister and Givoni (2013), which were previously discussed in section 2.2.

The approach of adapting the three shortest paths to include a station per city was done in the following way. The code creates a set that checks for urban areas along the paths of every pair of stations, while excluding the origin and destination area from this set and allowing areas to occur only once. If an urban area is added to the set, the path will be redirected to include a station of that area. It does so by generating shortest paths, for the assigned weight, to all stations in the area and selecting the station that provides the shortest possible detour from the initial shortest path. The detour is allowed to start from 4 edges before entering the urban area. If the adapted shortest path led to additional urban areas, the stations of those areas were also included in the path. This was ensured by using a while loop.

The application of this approach generated 1 to 3 shortest paths between every pair of stations of the 154 selected stations. The duplicates were removed by bundling the dictionaries of the separately generated shortest paths into one dictionary and removing the identical entries. A crucial step, since the shortest path based on in-vehicle time and disutility were frequently identical.

After bundling the unique shortest-paths per station pair, they were again bundled per city pair (OD-pair). This approach led to a number of paths between OD-pairs that varied strongly. In some cases, the path set contains 1 path. This occurs when all three generation approaches have generated the same path between a single pair of stations. The exceptionally high maximum is 72 paths between one OD-pair, which is Paris and Budapest. This can be explained by Paris having 8 stations in its urban area, Budapest having 3 stations in its urban area, and 3 paths that have been generated between every station pair. The multiplication of these 3 values leads to 72 paths that are not duplicates of each other, but are very alike. Most OD-pairs, however, contain two or three paths.

An example of a set of shortest paths per OD pair is presented in Figure 4.8, which contains the three shortest paths between Antwerpen (Belgium) and Tampere (Finland). Figure 4.8 shows neatly how the disutility path (path 3) is a trade-off between time and cost. Where path 1 takes the fastest path that is visually not the shortest, path 2 takes the shortest distance path along the Baltic Sea, and path 3 is situated precisely in the middle. Therefore, visually representing the trade-off.

The final step in generating the in-vehicle travel time matrix concerns appliance of the Path Size Logit model as presented in chapter 3. The probabilities per path are then used to calculate an average aggregated travel time- and utility matrix per OD-pair. How components of these attributes, like the transfer time, travel costs and travel time weights, are acquired is discussed in the following sections. The interpretation of the Path Size Factors and the corresponding probabilities is done in subsection 4.4.3.

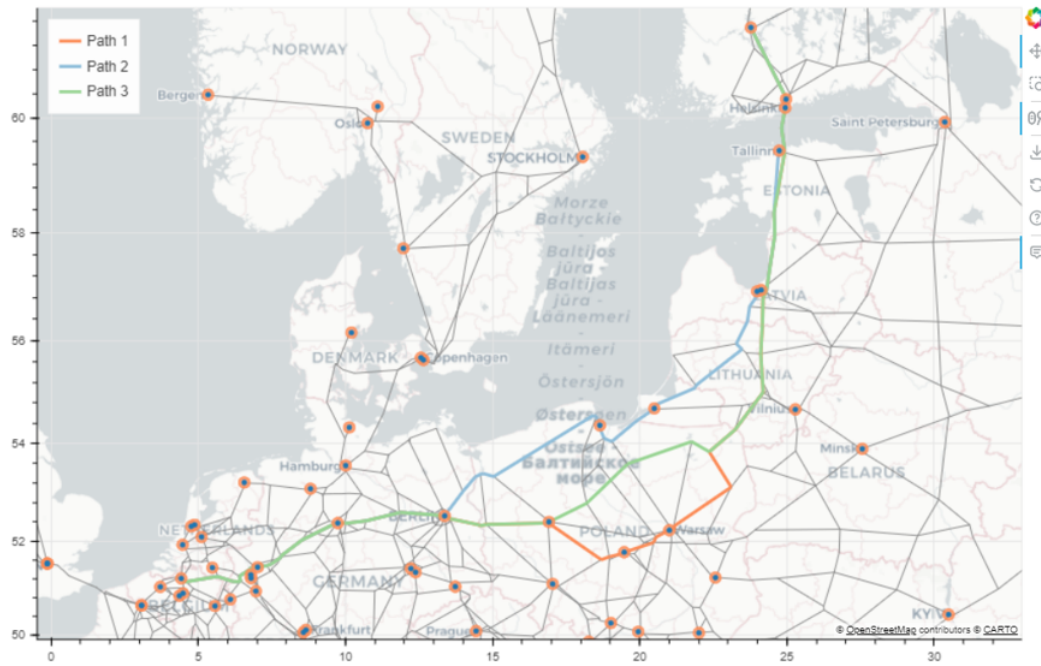


Figure 4.8: The three shortest paths for the Antwerpen-Tampere OD-pair. Path 1 is based on minimisation of time, path 2 of cost and path 3 of disutility. Created with Bokeh (Bokeh Development Team, 2018) in Python (Python Software Foundation, 2024). Background originates from OpenStreetMap (2024).

Transfer Times

The transport model used in this research does not account for services. This poses a challenge in estimating the number of transfers per trip as they are directly linked to railway services. However, excluding them entirely is not feasible. As discussed in the introduction, Europe's railway network currently consists of a 'patchwork' of railway operators, and it is unlikely that there will be a perfectly centralised railway operator or an integrated union of these operators by 2050 that would allow for direct routes across Europe. Moreover, it is questionable whether line services across Europe would be feasible from technical and financial perspectives. Excluding railway transfers would, therefore, result in an overly optimistic estimation of passenger distribution to rail in this model. Hence, this section adopts an approach where the number of rail transfers scales with distance. Additionally, this section includes a small additional implementation of transfers for the cities of Budapest, London, and Paris, as briefly discussed in the 'Edge Selection and Characteristics' subsection.

The literature review of this research has referenced the thesis published by Bruno (2022). It was noted in this literature review that, as of 2022, one would need at most seven transfers to travel between every pair of nodes in the EU by rail, whereas for air travel, it is only two transfers. Figure 4.9 indicates that while the maximum number of transfers in Europe was estimated to be 7, over 95% of OD pairs can be reached with only four transfers. This suggests that there are specific regions with limited service, likely situated at the outer edges of the continent where the rail system is constrained by geographical factors.

It is assumed that the distribution of transfer quantities over the set of OD pairs is roughly applicable to this research. This assumption is based on the fact that Bruno (2022) applies a set of 111 cities for his OD pairs, which are similar to the selected set of 124 cities in this research. Although the geographical scope of both studies is Europe, Bruno's scope is slightly smaller. Therefore, it is inherently assumed that the number of transfers per distance would be higher for the geographical scope of this thesis as per 2022. However, since the TEN-T network will further integrate Europe up until 2050, it is expected that this difference in transfers will be cancelled out. Furthermore, passengers on 5% of the paths in Bruno's study experience 5, 6, or 7 transfers. In line with the integration of Europe's railways,

this thesis assumes that the number of transfers experienced is capped at 5. Lastly, the conservative assumption is made that the number of transfers will not further improve up until 2050. The transfer times however were expected to improve, as discussed later in this section.

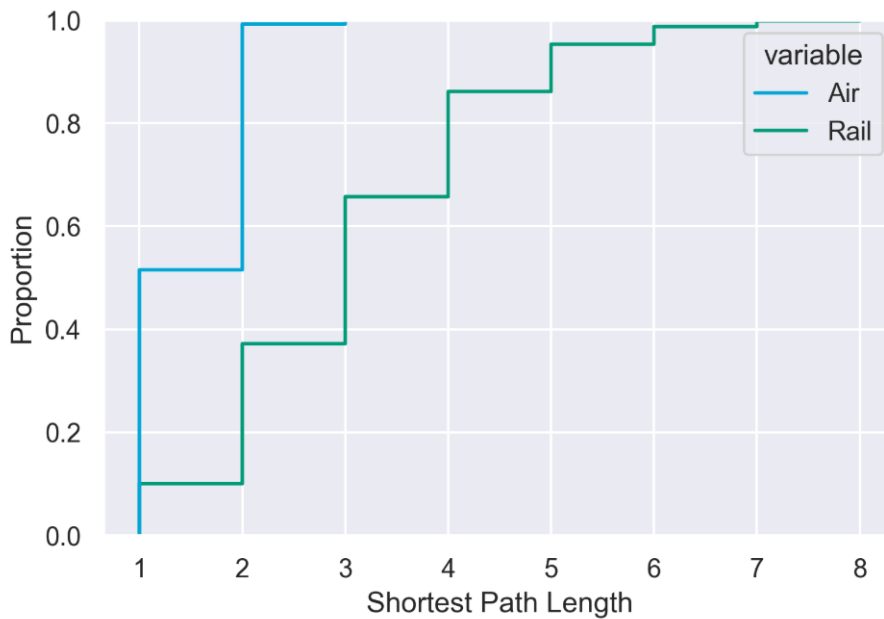


Figure 4.9: Cumulative Distribution Function concerning shortest path length for both rail and air in the context of European long-distance trips. Retrieved from Bruno (2022).

The procedure for applying thresholds of Bruno (2022) to this research, to create transfer thresholds per travelled distance, has been applied as follows:

1. The proportions of Bruno's total path set were rounded to the nearest five whole percentages, creating five thresholds for a range of 1-5 transfers based on the percentage of total paths. The resulting thresholds were 10%, 35%, 65%, 85%, and 95%.
2. The paths on which these thresholds would be applied were generated based on the minimisation of time. This choice was made because Bruno's shortest paths are primarily generated based on the minimisation of time, and partly on frequency, making this threshold approach more coherent than if applied to the shortest path for distance or disutility.
3. A list was created in Python that contained all the time-based shortest paths, and it was ordered by increasing distance.
4. The rounded percentiles were applied to the ordered list of paths. The first 10% of the trips in the distance-based list were estimated to use 0 transfers, those from 10% to 35% were assigned two transfers, and so on.

This procedure was applied five times to find the definitive set of transfer thresholds. The reason for applying this five times is that the generation of the shortest-path dictionary is slightly stochastic. This slight variance in results exists between runs in different kernels due to the nature of the Python sets used to dynamically store the urban areas in the while loop of the path generation. These slight anomalies occur in about 1 per 100 shortest paths. In the case of the generation with weight 'in-vehicle time', these anomalies effectively mean that paths are generated that are about 1 minute longer or shorter than the same path from another run. This difference comes from the order in which areas are processed and new areas are found. The consequences of this quasi-deterministic path generation approach and the arguments for why it is not changed to a deterministic, but slower, generation are provided in subsection 4.6.1.

Returning to the quantification of the distance-based transfer thresholds, the results of these five runs are presented in Table 4.7. The last column contains the definitive transfer thresholds per rail travel distance for this investigation. These transfer thresholds are visualised in a probability density function in Figure 4.10.

Thresholds	Run 1	Run 2	Run 3	Run 4	Run 5	Result
Trf. 1 [km]	527	527	527	527	527	527
Trf. 2 [km]	1189	1189	1189	1189	1189	1189
Trf. 3 [km]	1930	1931	1930	1930	1930	1930
Trf. 4 [km]	2603	2602	2603	2602	2603	2603
Trf. 5 [km]	3243	3243	3243	3243	3243	3243

Table 4.7: Transfer threshold values per distance for different runs of the shortest path generation.

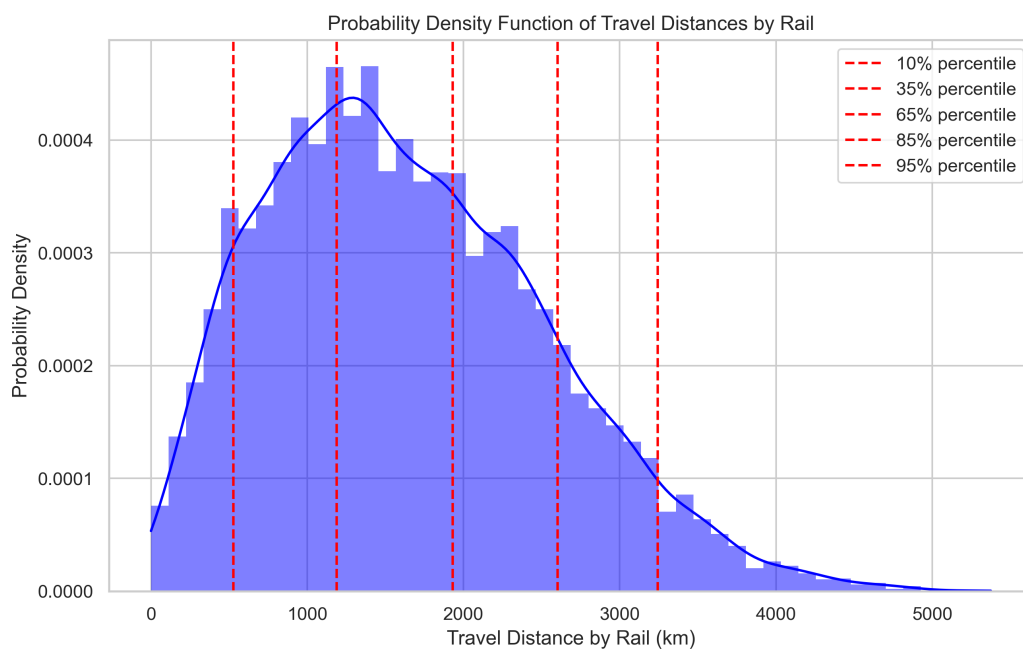


Figure 4.10: Probability density function of rail travel distances in the network and the transfer thresholds for the distances in accordance to Table 4.7.

The resulting transfer thresholds were applied in the Python code to determine per path how many transfers are used, based on the distance of the path. The corresponding time per transfer was presumed take approximately 30 minutes. This duration was derived from the research of Grolle (2024) Grolle et al. (2024), who assigns 30 minutes for transfers under centralised organisation, in contrast to the 60 minutes allocated for long-distance transfers in a free market setting. The rationale behind adopting this relatively brief 30-minute transfer time is the anticipation of future optimisation in train schedules for long-distance travel, where adjustments will be made to synchronise services more effectively. Thereby creating a long-distance network with smart transfers. This assumption is supported by the EU's pursuit of 'seamless transit' through the TEN-T policy European Commission (2021b), with the potential for reduced transfer times to contribute to its partial fulfilment.

Lastly, there is one other case in which transfers lead to transfer times. In essence, all of the transfers described above are 30-minute transfers that happen within a station from one platform to the other. In three city cases, which have been previously mentioned in the edge selection section, there are,

however, also transfers that occur through the city between stations. This situation occurs between the long-distance terminus stations of Budapest, London and Paris. The inner city transfer travel speeds were based on that of the urban access/exit speed, which is 19km/h. The transfers were included as edges with a speed of 19km/h within the QGIS railway network shapefile.

Waiting Time

The waiting time is assumed to be 15 minutes for initiating a long-distance rail journey, since in general no elaborate check-in systems are present at railway stations. In most cases, passengers can just scan their ticket and move to their platform of destination. The specification of waiting time for rail is the last component that had to be provided to generate the aggregated travel time in accordance to Equation 3.7.

Just like other assumptions in this thesis, the assumption in the previous paragraph is a generalisation and it might very well be shorter or longer, varying from groups of individuals and countries of origin. One of the main potential causes for it to be longer lies in border control, leading to passengers that incorporate waiting times at customs into their time of arrival. This effect is not expected to be large since the Schengen area covers most of the geographical scope, but it is included and discussed in subsection 4.6.3, which is the limitations section of this chapter.

Travel Costs

The second attribute that had to be estimated per mode, next to the aggregated travel time, is the travel cost, as it is the most important attribute next to travel time (Zhang, Yang, and Wang, 2017). Forecasting travel prices is inherently uncertain, but not including prices at all heavily reduces realism. Exclusion of costs would implicitly mean that the costs of travelling by train, plane and car are assumed equal. This has been untrue for 2022 (Tanner, 2023), as the travel cost sections in this chapter will show quantitatively, and is expected to become further from the truth until 2050 in the face of intended EU carbon policies on internalising carbon emission externalities in the price of mobility. These policy plans are discussed later in this section.

The initial starting point for estimating this per mode was Tanner (2023), who defines in his research a similar OD-matrix for long-distance travel in Europe and uses an extensive web-scraping method to find the costs between these pairs for the year 2022. Since his method is comprehensive in comparison to other sources and the data is from a recent year, it was applied to estimate travel cost for every mode, i.e. train, plane and car, in this chapter.

The travel costs for rail were estimated to have been on average 0.118 € per kilometre travelled Tanner (2023) in 2022. This value was computed by applying the Haversine function of Equation 4.1 to calculate the geodistances for all of Tanner's OD-pairs, leading to a cost of 0.154 €/km per distance as the crow flies for every OD-pair. Averaging this and applying a detour factor of 1.3 for train (Tanner, 2023) has led to a cost of 0.118 €/km travelled.

The previously mentioned Haversine formula is used for calculating the great-circle distance between two points on a sphere, given their longitudes and latitudes. The formula considers the shortest path over the Earth's curvature, providing a more accurate measurement of distance for mapping and navigation purposes than a straight line through the Earth, and can be written as:

$$d_{ij} = 2R_e \arcsin \left(\sqrt{\sin^2 \left(\frac{\varphi_i - \varphi_j}{2} \right) + \cos(\varphi_i) \cos(\varphi_j) \sin^2 \left(\frac{\lambda_i - \lambda_j}{2} \right)} \right) \quad (4.1)$$

Where:

- d_{ij} is the distance between points i and j .
- φ_i and φ_j are the latitudes of the points i and j , respectively.
- λ_i and λ_j are the longitudes of the points i and j , respectively.
- R_e is the radius of the Earth, which is approximately 6371 km.

Other studies that model the future HSR-network have assumed that long-distance travel costs will not change disruptively in Europe and that no disruptive (policy) changes will take place in that context (PTV Group, 2023; EY, 2023). This thesis assumes otherwise and includes a price change due to the implementation of a form of carbon emission pricing policy. This decision was made since the EU explicitly assumes that carbon pricing instruments will be implemented (European Commission, 2021a).

Tanner (2023)'s research aims to study the impact of a Tradable Mobility Credit (TMC) system on the modal split for long-distance leisure travel in Europe. Such a TMC system is comparable to the European Emission Trading System (ETS) in its goals, but the difference is that in firms can trade emission rights in ETS and individual people are able to in TMC Tanner (2023).

For this research, it is assumed that the EU will internalise carbon emission externalities in the price of mobility, since the TEN-T policy entails carbon pricing instruments in the reference scenario of its impact assessment (European Commission, 2021b; European Commission, 2021a). The authors state that an ETS and the infrastructure policies (TEN-T) will together deliver the EU's transport sustainability goals.

This research applies the implementation of a TMC with a conservative reduction target to include effects that are similar to the EU ETS policy. A consideration in this decision was that the forecast price effects of TMC are readily available from research of Tanner (2023) and the system is sufficiently comparable to ETS in its goals and, in particular, the intended price effects. Tanner's research clearly shows these expected price effects; namely that plane tickets are most affected by the policy, and rail tickets are least affected.

Although the EU aims to be CO₂-neutral by 2050, this paper assumes a conservative TMC that aims for a 30% reduction target. This is done since almost no planes would be left in the modal split if a TMC corresponding to a 90% reduction target was incorporated into the model Tanner (2023), which would lead to a potentially large overestimation of the rail mode. This approach is in line with a common practice in forecasting; and that is to be conservative (Armstrong, Green, and Graefe, 2015). The publication by Armstrong, Green, and Graefe (2015) advocates conservative evidence-based forecasting, and recommends to limit the amount of change in the face of uncertainty. Their advice was taken to heart in the specification of this conservative reduction target, since the authors define policies under the category 'uncertain'.

The TMC with a target reduction of 30% leads to a price increase of about 8% for rail, according to Tanner (2023). Combining this with an inflation rate per year of 2%, as assumed by EY (2023), between 2022 and 2050 leads to an estimated rail price of 0.22 €/km for 2050.

4.2.2. Air Network

This section investigates air travel in Europe by 2050, focusing on the estimation of air travel attributes. The section entails the selection of airports, the specification of access/egress times, the specification of in-vehicle travel times, and the estimation of travel costs. Notably, the possibility of transfers is excluded, and the rationale for this decision is discussed in the subsequent airport subsection.

Airport Selection

Since air travel is not the main focus of this thesis, but rather a means of estimating the modal split and rail passenger volumes for 2050, data was largely assumed from existing sources. The principal source for quantifying air travel attributes was Grolle et al. (2024), chosen over other studies such as Borgogno (2023) and Tanner (2023), because it includes service-specific data. Unlike Borgogno (2023) and Tanner (2023), who assume that all airports in their sets are connected by flight paths, Grolle et al. (2024) utilises passenger carriage data from Eurostat (2023) to create an OD-passenger matrix for 124 cities. This set of 124 cities was also applied in this research, as justified in an earlier section. In addition, all datafiles of Grolle et al. (2024) are openly available, which made this research feasible for use in this research.

Grolle et al. (2024) constructed a symmetric OD matrix between 384 European airports using a combi-

nation of Eurostat (2023) questionnaire results and additional sources. Visual inspection of the 2020 air passenger distribution matrix revealed that the assumptions made by Borgogno (2023) and Tanner (2023) are overly simplistic. Many airport pairs in the 2020 dataset lack passenger flows, suggesting that assuming flight paths between all cities would significantly overestimate air travel in a transport model. Therefore, Grolle et al. (2024)'s data was used for estimating various air travel attributes. This inherently means that services were assumed to remain the same up until 2050, but since no reliable prediction can be made, the best that one can do is apply the *ceteris paribus* principle. Consequently, 384 airports are included in this study, as shown in Figure 4.11.

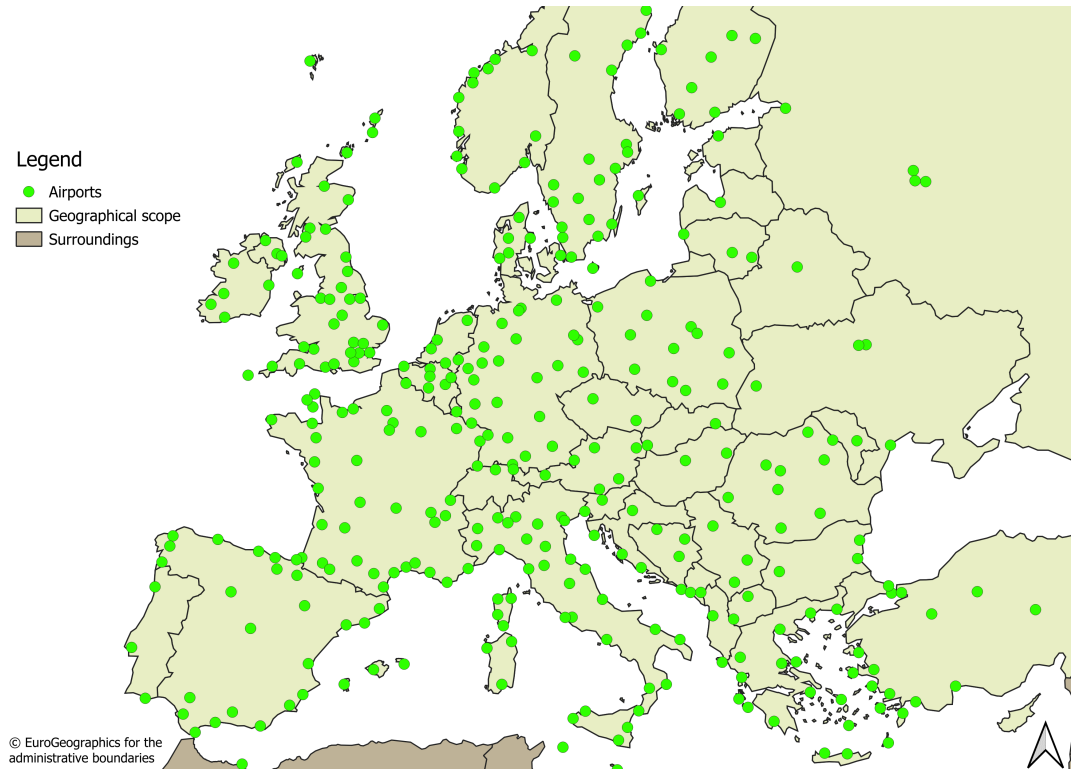


Figure 4.11: Airport selection in Europe.
National borders are adapted from Eurostat (2020a) data. Created with QGIS (2023).

None of the studies discussed in this section, including Borgogno (2023), Tanner (2023), and Grolle et al. (2024), entail the possibility of transfers, an assumption which is also adopted in this thesis. This assumption is not expected to underestimate air travel, as the approach from Grolle et al. (2024) allows passengers to travel up to 2.5 hours by car to an airport with a route to their preferred destination. This is illustrated with chronomaps in Figure 4.12 in the next subsection on access/egress times.

Access/Egress Times

This section defines the applied procedure for generating the access and egress time OD-matrices, which were then be used in the transport model.

The starting point was, based on the arguments in the previous section, the approach of Grolle et al. (2024). That research assumes that people are willing to travel at maximum 2.5 hours by car to access or egress an airport. This is a constraint that was driven by estimation of passenger willingness, but also driven by the aim of limiting the computational burden. Applying this constraint to a set of 384 airports means that passengers usually have many flight paths to choose from when travelling an OD-pair. The chronomaps for these 2.5-hour car rides are presented in Figure 4.12 for a trip between London and Rotterdam. Airports within the 2.5-hour perimeter are considered feasible for a flight to any destination, thus forming the city-airport system for a specific city. This research applied an adapted

version of the Python file on 'Module Demand Estimation' of Grolle et al. (2024) to estimate the probabilities of taking a specific flight trip in accordance with the MNL probability function. The way in which it was adapted is described later in this subsection.

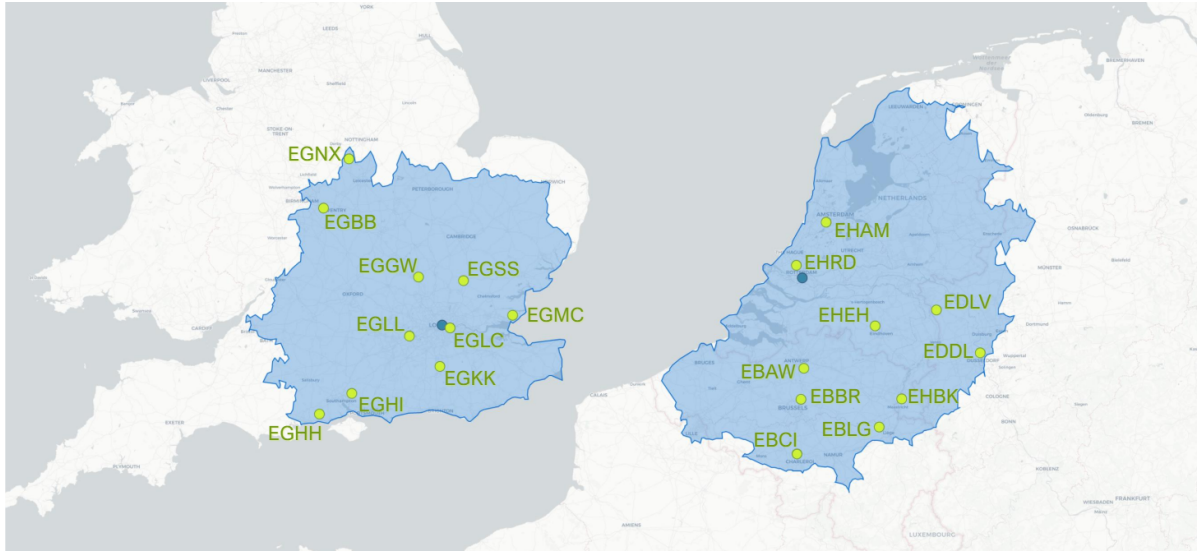


Figure 4.12: City-airport systems for London and Rotterdam. Figure adapted from Grolle et al. (2024).

There is, however, one issue with directly applying Grolle et al. (2024). Literature shows that the modal split of passengers accessing and egressing an airport is generally divided between road (i.e. car and taxi) and public transport, with shares of 0.65 and 0.35, respectively. These findings from literature are presented in Table 4.8. The research by Grolle et al. (2024), however, assumes that all access and egress trips are made by car. Albeit that the car travel times are defined realistically through applicance of the API of OpenRouteService (ORS) Heidelberg Institute for Geoinformation Technology (2022), which finds the fastest possible route by car between two locations based on their coordinates using the existing road network.

Country	IATA	Year	Road	PT	Source
GR	ATH	2002	0.9	0.1	Psaraki and Abacoumkin (2002)
FR	ORY	2002	0.7	0.3	
NL	AMS	2002	0.54	0.46	
DE	FRA	2002	0.65	0.35	
SW	ARL	2003	0.56	0.42	Kouwenhoven (2009)
UK	LHR	2004	0.64	0.36	
UK	LGW	2004	0.69	0.32	
NO	OSL	2005	0.4	0.6	
DE	Several	2008	0.71	0.29	DLR (2010)
ES	Several	2019	0.68	0.32	
NL	EIN	2020	0.67	0.33	Colovic et al. (2022)
					Reshad (2020)

Table 4.8: Mode choice behaviour across different European airports in the 2000s.

Based on Table 4.8, it was decided to incorporate both access and egress trips via car and via PT with shares of respectively 0.65 and 0.35. A secondary aim, however, was to retain the realistic car data from the ORS approach (Grolle et al., 2024). Retaining the car approach via ORS also meant that the 2.5-hour car perimeter per city-airport system, as in Figure 4.12, had to be maintained for access/egress via PT for consistency.

This approach did have implications. Application of the car data from Grolle et al. (2024), which assumes the city centre as base point, is not entirely consistent with the access and egress approach for rail, where a weighted access/egress distance was determined based on the Geostat 1km² population grid of Eurostat (2020a). Applying the population-weighted average access/egress distance method would be more realistic than calculating the (great-circle) distance and travel time between a single point, i.e. the city centre, and an airport. However, several considerations applied in including the car trip data:

1. It is very labour-intensive to set up the population-weighted method for 124 cities, which in some cases have access to dozens of airports within a 2.5-hour travel range.
2. Since 65% of the journeys are taken by car, it is deemed more crucial to factor in roads and typical traffic conditions when calculating travel times, rather than modelling the start/end points of a car access/egress journey realistically. Assuming the city centre as the starting point is a practical approximation given the scale and distances involved.
3. The assignment of airports from various directions around a city distributes the potential error of assuming the city centre as the urban starting point. In other words, the presence of multiple airports might balance out the access/egress distances.

Since it was decided that no population-weighted access/egress distance approach would be executed for car trips within the 2.5 hour perimeter, there is also no weighted access/egress geodistance for air passengers using PT. Fortunately, the dataset of Grolle et al. (2024) contains an Excel file with all city-to-airport distances, which are used for public transport-using air passengers.

The speeds for accessing or egressing an airport are based on Rothfeld et al. (2019), which provides linear regression models for access and egress speeds in the context of European airports. The proposed regression model relies on variables that were available in this research, such as the access/egress geodistance, whether it is access or egress, and whether it is day or night. The regression model also contains a binary for night trains, but this was set to 0 since night trains have been assumed to be negligible. The corresponding graph that illustrates the speed per geodistance is provided in Figure 4.13. Applying this to the corresponding city-to-airport matrix entries granted the access/egress duration per city-to-airport trip.

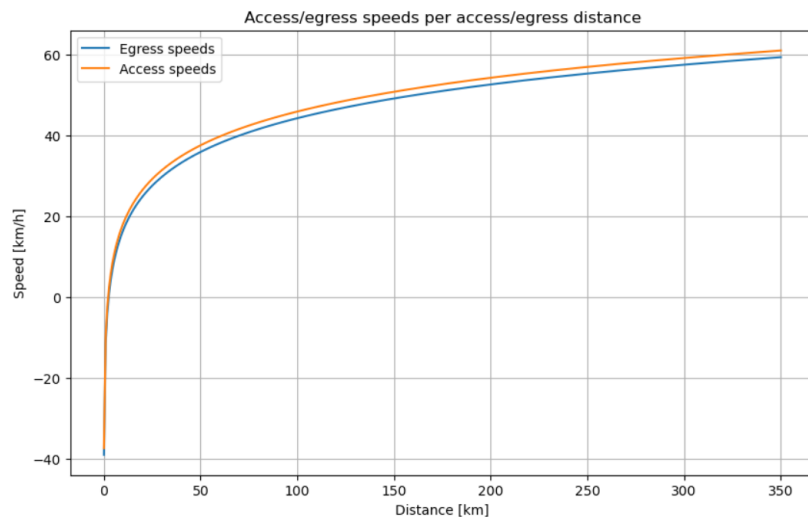


Figure 4.13: Average access/egress speeds per access/egress distances (Rothfeld et al., 2019).

The generated city-to-airport trip durations for PT were combined with the city-to-airport car durations using the modal shares presented in Table 4.9. This was done in the previously described Python file

from Grolle et al. (2024). Analysis of the new access/egress durations illustrated an overall increase by adding PT as a city-to-airport mode according to Table 4.8. An overview of the steps and sources used to generate the mode-specific trip durations is provided in Table 4.9.

Table 4.9: Approach for access/egress estimation for airports.

Mode	Shares	Detour	Speed (travelled dist.)	Geodistance	Duration
Car	0.65	-	-	-	ORS via Grolle et al. (2024)
PT	0.35	1.6	Rothfeld et al. (2019)	Grolle et al. (2024)	<i>Computed in Python</i>

14 exceptions to the described access and egress procedure exist in the resulting dataset. These exceptions were made to provide consistency with the access/egress times of the peripheral HSR-stations that are located at airports. The access/egress times of peripheral HSR-stations at airports, as generated in the railway approach (RA) through QGIS (2023), were compared with the access/egress times from the adapted airport approach (AA) of Grolle et al. (2024). This comparison specifically concerns the access/egress times for trips that take place within catchment areas where HSR-stations are located at airports, since rail passengers only start their long-distance travels in the catchment area where they live. In addition, it is assumed that principally, the the RA (QGIS approach) is more accurate for its use of weighted access/egress distance determination through population density.

In 14 out of 15 of the peripheral HSR-stations, the access/egress time of the rail approach (RA) was selected to apply for both the HSR-station as the airport. In 1 out of 15 cases, the case of Oslo, the access/egress time of Oslo of the airport approach (AA) is selected to apply for both the HSR-station as the airport. The results are presented in Table 4.10.

Table 4.10: Access/egress time comparisons according to airport approach (AA) and rail approach (RA), including the resulting access/egress times for the combined air-HSR-hubs.

City	Airport	Acc/egr AA [h]	Acc/egr RA [h]	Result acc/egr [h]
Amsterdam	Schiphol Airport	0.66 / 0.68	0.48	0.48
Birmingham	Birmingham International Airport	0.72 / 0.75	0.77	0.77
Brussels	Brussels Airport	0.60 / 0.62	0.56	0.56
Copenhagen	Copenhagen Kastrup Airport	0.68 / 0.71	0.83	0.83
Dusseldorf	Dusseldorf Airport	0.57 / 0.59	0.36	0.36
Frankfurt	Frankfurt am Main Airport	0.59 / 0.62	0.72	0.72
Helsinki	Helsinki Vantaa Airport	0.76 / 0.79	0.55	0.55
Leipzig	Leipzig/Halle Airport	0.70 / 0.73	0.59	0.59
Lyon	Lyon Saint-Exupery Airport	0.80 / 0.84	0.76	0.76
Madrid	Adolfo Suarez Madrid-Barajas Airport	0.65 / 0.67	0.64	0.64
Oslo	Oslo Gardermoen Airport	1.22 / 1.27	1.50	1.25
Paris	Charles de Gaulle	0.71 / 0.74	0.59	0.59
Riga	Riga International Airport	0.65 / 0.67	0.44	0.44
Vienna	Vienna International Airport	0.69 / 0.72	0.72	0.72

A number of considerations applied to the creation of Table 4.10:

- The expectation was that the railway approach (RA) for access/egress would provide faster access/egress times than the airport approach (AA), due to the assumed PT transit connections that are incorporated in the RA but not in the AA. Therefore leading to an improvement of airport accessibility. This turned out to be true in 9 out of 14 cases for airports with HSR closure in the baseline model. The exceptions were Birmingham, Copenhagen, Frankfurt, Vienna, and Oslo.
- The reason for a faster/more favourable access time for Birmingham, Copenhagen, and Frankfurt is due to the simplistic determination of access/egress distance of the AA approach. The city-to-airport distance matrix of Grolle et al. (2024) contains distances that were on average two times as low for these three cities than they were estimated in the RA. The access/egress times of the AA approach are therefore considered less accurate. The resulting access/egress times for these three airports are therefore set to the results of the RA.

- In the case of Vienna, the airport's access/egress times of AA are very similar to that of RA, with a slightly higher average access/egress distance in RA. Since they are very close, but the RA is assumed to be more accurate, the resulting access/egress for the airport was set to that of RA, thereby providing consistency.
- Oslo airport is the odd one out. The estimated access/egress distances were close, but AA estimates a much faster access/egress time. This can be explained by the use of the ORS API (Heidelberg Institute for Geoinformation Technology, 2022) in the AA based on Grolle et al. (2024), which models the car mode more accurately than RA. While inspecting the map of Oslo, one sees that there is a relatively straight highway between Oslo city and the airport (Google Inc., 2024). The RA assumes an average speed of 27 km/h to peripheral stations across all modes, which is expected to be too slow for a context where 65% of the access/egress travel is by car, and where the car can largely take a highway with a low detour factor. This is why the access/egress value was set to 1.25 hours, which is very close to the original value of the AA, but slightly higher due to the higher weighted access/egress distance of the RA. Both the access and egress time for the peripheral HSR-station and the city-to-airport time were set to 1.25 hours.

After generating the combined access and egress times for the entire city-to-airport trip dataset, the adapted code from Grolle et al. (2024) was executed to provide probabilities of taking a certain flight route using MNL. The definitive access and egress times per OD-pair were generated by applying the probabilities per flight route to the corresponding data, thus generating the average access and egress durations.

Lastly, the application of MNL for the flight route assignment is consistent with the PSL method of the rail route assignment, since if PSL were applied in the plane context, it would effectively be MNL because they are 100% different (no infrastructure piece is the same). This leads to a Path Size Factor that represents zero overlap.

In-vehicle Travel Times

The in-vehicle travel times for airplane trips were adopted directly from Grolle et al. (2024). They were assumed to be relatively unchanged by adding the PT mode as an option for access/egress. Comparison of the results between the original in-vehicle time matrix and some of the adapted code results illustrated only minor differences. As stated at the beginning of this section, it is assumed that the air services will not change, which makes this dataset directly applicable.

Waiting Times

The last element necessary for generating the aggregated travel time for air travel is the waiting time. The waiting time is assumed to be 110 minutes per flight trip, in accordance with Park and Ahn (2003), who found that passengers for short-haul flights on average arrive between 100 and 120 minutes before the scheduled departure.

Travel Costs

The applied approach for calculating the travel costs per kilometre is the same as previously in the rail section. This means that a Tradable Mobility Credit policy with a reduction target of 30% was applied to the 2022 results of Tanner (2023), with a yearly average inflation rate of 2% (EY, 2023). A large difference in comparison to the rail subsection on costs is that the detour factor of aeroplanes is assumed to be 1.0, meaning that the distance that a plane travels is assumed to be the same as the distance as the crow flies.

Recent air travel costs were acquired from Tanner (2023) and averaged to an estimate of 0.137 €/km for 2022. The TMC with 30% reduction target increases the price of air with approximately 38%, according to Tanner (2023). Combining this with a yearly inflation rate of 2% between 2022 and 2050 led to an estimated plane travel cost of 0.33 €/km for 2050.

4.2.3. Road Network

In-vehicle Travel Times

The in-vehicle travel times for car were directly adopted from Grolle et al. (2024), who generated them with the previously described ORS software. This dataset was directly applicable since this research

assumes the same 124 urban nodes. An additional time factor of 10% was added to these values to include breaks, which will have to be taken during long-distance car travels. This 10% was processed as normal in-vehicle time with the corresponding weight of Table 4.11, since it is assumed that people do not dislike a car break as much as they dislike waiting time at an airport or train station.

Travel Costs

The applied approach for calculating the travel costs per travelled kilometre roughly is the same as previously in the rail and air section. In other words, a Tradable Mobility Credit policy with the aim of 30% reduction was applied on the acquired 2022 travel costs of Tanner (2023) and a yearly average inflation rate of 2% by EY (2023).

Recent car travel costs were acquired from Tanner (2023) and were estimated to be on average 0.137 €/km travelled in 2022. Tanner estimates car travel costs based on fuel pricing in origin countries and destination countries, fuel consumption, toll roads, and average car occupancy in 2021 and 2022. Ownership, maintenance, and purchase costs are not included.

The TMC with 30% reduction target increases the price of the car per km with about 18%, according to Tanner (2023). Combining this with a yearly average inflation rate of 2% between 2022 and 2050 led to an estimated car travel price of 0.30 €/km for 2050.

4.3. Choice Parameters

4.3.1. Weights for Aggregated Travel Time

Equation 3.7 of the methodology was applied in the transport model to capture the various stages of a long-distance journey, segmenting the door-to-door journey into access time, waiting time, in-vehicle time, egress time, and transfer time. As highlighted by Ramjerdi (2010), a single value of time is insufficient to accurately represent the differences between these distinct stages. Therefore, in this study, five travel time weights were assigned to five distinct stages of long-distance travel.

The ω values used in this analysis are derived from Grolle et al. (2024), which derived them from the findings of Ramjerdi (2010), and are presented in Table 4.11.

Table 4.11: Travel time weights per trip component. Based on Ramjerdi (2010).

	Access	Waiting	In-vehicle	Transfer	Egress
Weight [-]	1.36	1.50	1.00	1.50	1.36

4.3.2. Values of Time

An estimate for the Values of Time in Europe per 2024 and 2050 was made on the basis of the meta-analysis of Wardman et al. (2012). This meta-analysis is very extensive and contains Value of Times per long-distance mode and per country, as they were estimated in 2010. The weighted average Value of Time for Europe for the base year of 2024 is estimated to be €25.44. The weights used to compute this average were the national population sizes of Eglitis (2024). The result includes an inflation correction factor of on average 2.27% per year between 2010 and 2024 (Eurostat, 2020a), which was defined as the reference year of this research in section 1.7. This process is mathematically presented in Equation 4.2.

$$\text{VoT}_{2024} = \frac{\sum_{i=1}^n (\text{VoT}_{2010,i} \times \text{Pop}_i) \times (1 + \text{Inf}_{\text{avg}})^t}{\sum_{i=1}^n \text{Pop}_i} \quad (4.2)$$

Where:

- VoT_{2024} is the weighted average Value of Time for Europe in 2024.
- $\text{VoT}_{2010,i}$ is the average Value of Time for country i in 2010. Based on taking the average of the car-specific VoT, the train-specific VoT and the plane-specific VoT.
- Pop_i is the population of country i .
- Inf_{avg} is the average annual inflation correction factor (2.27%).

- t is the number of years between 2010 and 2024, which is 14.
- n is the number of countries considered, which is 34.

Wardman et al. (2012) describe how GDP/Capita is the variable that explains away most of the VoT developments, with a coefficient for elasticity of 0.72 and a very precise confidence interval of about 15%. This is why this research applied this coefficient as an approach to estimate the Value of Time for 2050.

The population of the EU per 2024 is estimated to be 452.9 million (Eurostat, 2020b) and is predicted to decrease to 447.9 million in 2050. This means that the growth factor for capita is 0.99. PWC (2017) estimates that the GDP will increase by 1.1% per year up to 2030, 1.2% per year between 2030-2040, and 1.3% per year between 2040-2050. These estimates of PWC (2017) are adjusted for price level differences among the various EU countries. Together, the growth factors effectively contribute to a projected GDP growth of 74% up until 2050.

Therefore, GDP/Capita was estimated to increase with 76% between 2024 and 2050. Multiplication of the elasticity factor of 0.72 with the expected growth of GDP/Capita provided an expected increase of VoT of 54% for the time window of 2024-2050. In conclusion, it was estimated that the VoT will increase from €25 in 2024 to €39 in 2050. Although this data largely originates from sources concerning the EU, it is assumed that these final results are coherent for the entire geographical scope.

4.3.3. Choice model parameters

This section contains the approach and results in determining the RUM-choice parameters for the third step of the 4-Step Transport Modal, i.e. the modal split. Estimates were made through a literature study, after which they are verified with the modal split of previous study.

The literature study was conducted to estimate the desired RUM choice parameters in the context of long-distance travel. The selection of publications was limited to literature that complies with the following constraints:

- The publication estimates RUM choice parameters based on reliable mode choice data, such as a Stated Preference survey.
- The mode choice data used to estimate the parameters explicitly refer to long-distance travel.
- The estimation of choice parameters must include both travel time and travel cost attributes. The presence of these two attributes is essential, as their ratio reflects the trade-off travellers make in decision-making.

On top of these constraints, there were a few objectives:

- The mode choice data originates from a relatively recent year.
- The mode choice data was recorded preferably in Europe.
- The RUM parameter estimates include alternative specific constants (ASC). This is preferred since ASCs represent the utility that is associated with factors other than the observed attributes. Essentially, incorporating these based on literature adds to the realism of this research's transport model.
- For reliability, a large number of literature sources was preferred.

The results of this literature study are presented in Table 4.12. Every selected publication contained generic choice parameters for travel time and travel cost that were estimated for all modes of that study. These parameters are presented respectively in the columns called β_{TT} and β_{TC} . The reader can deduce from the ASC columns which modes for long-distance travel were considered per study.

Satisfying the defined objectives turned out to be tricky, since not many RUM-parameter estimation studies on long-distance travel could be found. The scope was therefore expanded to areas outside of Europe and data from less recent years. NB: The included modes often vary compared to the three defined for this study in section 1.7, being rail, air, and road. However, all modes per paper were included in Table 4.12 for completeness. The abbreviation 'conv' in this table stands for conventional rail.

The last row of Table 4.12 contains averages for all parameters for which more than two were found. The Value of Time average, in the lower right corner, was determined by using the average β_{TC} and average β_{TT} in coherence with Equation 4.3. It was not determined by using the average Value of Times of the six selected literature sources, which have varying types of valuta.

Table 4.12: Literature analysis of RUM parameter estimations for long-distance travel, based on respectively:

1. Koppelman and Wen (2000); 2. De Bok et al. (2023); 3. California High-Speed Rail Authority (2016); 4. Lapparent, Frei, and Axhausen (2009); 5. Oña et al. (2023); 6. Abouelela et al. (2022).

	Year	Country	Type	β_{TT}	β_{TC}	ASC_{car}	ASC_{bus}	ASC_{air}	ASC_{HSR}	ASC_{conv}	VoT	Unit
1	1989	Canada	Business	-0.01	-0.04	0	N/A	3.644	1.67	N/A	12.99	C\$/h
2	1999	Portugal	HSR	-0.02	-0.07	3.49	0.38	N/A	0.00	N/A	12.63	EUR/h
3	2005	USA	<i>mixed</i>	-0.01	-0.02	4.03	N/A	-4.86	2.05	-2.34	19.50	US\$/h
4	2009	Czech	<i>mixed</i>	-2.02	-6.98	0	1.87	-14.5	0.70	N/A	17.36	EUR/h
5	2013	Brazil	<i>mixed</i>	-0.01	-0.03	0.87	0.61	-2.11	0.00	N/A	20.00	BRI/h
6	2022	Germany	Air	-0.01	-0.04	N/A	N/A	N/A	-0.8	N/A	14.00	EUR/h
6	2022	Germany	Rail	-0.01	-0.01	N/A	N/A	-5.48	N/A	N/A	40.00	EUR/h
			Average	-0.30	-1.03	1.68	0.96	-4.66	0.60	N/A	17.35	valuta/h

The Value of Time column of this table was estimated based on Equation 4.3, which is true when utility is a linear function of travel time as well as travel cost. This linearity applies when only TT and TC are included, like in this thesis. The units for the parameters in Equation 4.3 are [utils/valuta] for β_{TC} , and [utils/h] for β_{TT} . The reader should take note that the β_{TT} in Table 4.12 has as unit [utils/min].

$$VoT = \frac{\partial V}{\partial T} = \frac{\frac{\partial V}{\partial T}}{\frac{\partial V}{\partial C}} = \frac{\beta_{TT}}{\beta_{TC}} \quad (4.3)$$

It was stated in the methodology that "every ASC should have a theoretical underpinning, meaning that one can understand its negative or positive influence". This statement was used to verify the logic of two values in Table 4.12. The table illustrates how the car is initially a very attractive mode option, having the highest positive ASC. This interpretation fits the statement of European Court of Auditors (2018b) that the car is dominant transport mode on journeys of less than 200 km. Air on the other hand has a very negative average ASC, but the mode will become more competitive on longer distances since it is faster than the alternative modes and will therefore be less impacted by the β_{TT} . This again fits statements by European Court of Auditors (2018b).

The ASCs were also verified with the modal split results of Donners (2016), which estimated a modal split of long-distance travel in Europe for multiple scenarios. Donners' modal split is presented in Figure 4.14, showing y-axis intercepts that mostly resonate with the statements of the previous paragraph and Table 4.12. One can see in the 2015 base scenario of Figure 4.14, which is the most applicable scenario for this research, that the plane is initially the most unattractive mode to take. The distinctly negative ASC for air of Table 4.12 therefore makes sense, corresponding to a poorly performing air mode in Figure 4.14.

Figure 4.14 also clearly shows that the car and train in market share are only about 4% apart from each other. This relatively small difference can also be found in Table 4.12, although the car is the better alternative there. However, it was assumed for this research that the results from Table 4.12 are more likely to be more correct than Figure 4.14. The decision to select the results of the literature study over the modal split of Donners was based on the argument discussed earlier in European Court of Auditors (2018b), stating that the car is the dominant mode up to long-distance trips of 200 km. Therefore, a higher intercept (ASC) is required for car than for rail, which is exactly what Table 4.12 contains.

The choice parameters β of Table 4.12 could not be compared on the basis of visual inspection of Figure 4.14. Neither could they be compared with other results from Donners (2016). The reason for this is that Donners' model forecasts are merely based on the attribute of travel time, and does not include travel cost.

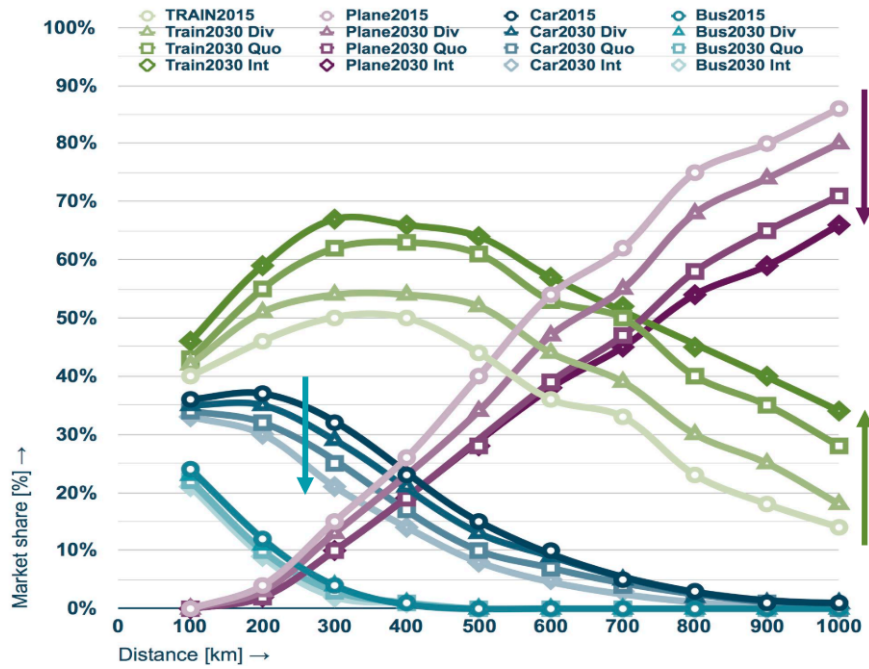


Figure 4.14: Modal split in European long-distance travel for three scenarios according to Donners (2016).

The Values of Time as calculated in subsection 4.3.2 differ quite a lot from the values in Table 4.12. In subsection 4.3.2 it was estimated that the VoT for the geographical scope of this research is €25 in 2024 to €39 in 2050. The value of 39 should therefore be the ratio of the time- and cost-parameter when estimating long-distance passenger transportation in Europe 2050. Note that the value of β_{TT} is in [utils/min] in Table 4.12 and must be applied in [utils/h] in Equation 4.3 when realising that ratio.

The β_{TC} is altered to realise this ratio between β_{TT} and β_{TC} . The ASCs are however assumed to remain the same as the averages of Table 4.12, based on the analysis in previous paragraphs, and are rounded off to the nearest half. This generates the following definitive list of β and ASC choice parameters.

Table 4.13: The definitive list of choice parameters.

Parameter	Value
β_{TT}	-0.030
β_{TC}	-0.045
ASC_{car}	1.0
ASC_{air}	-5.0
ASC_{train}	0.0

Table 4.12, the final result of this section, assumes that choice parameters are consistent across all modes. However, literature analysis in section 2.2 has previously identified that the satisfaction of passengers can also influenced by the mode itself Zhen, Cao, and Tang (2018). The context in which Zhen, Cao, and Tang (2018) have put this forward was an analysis of access and egress in the context of HSR-stations, stating that car leads in passenger satisfaction for egress trips, followed by rail transit, taxi and bus. This publication suggests that in reality, different choice parameters would exist across different modes in the context of long-distance travel. This assumption is therefore included in subsection 4.6.3.

4.4. Results of the Transport Model

This section presents the results of the application of the combined mode-route choice model, as presented in chapter 3, with the previously defined inputs of this chapter.

4.4.1. Trip Distribution 2050

This thesis adopts the trip distribution dataset from Grolle et al. (2024) as a starting point and extrapolates it to the prediction year of 2050. Grolle et al. (2024) used airport traffic data for 2019 in combination with estimated market shares for air mode to create a refined OD-matrix. Since their OD-set is directly adopted in this thesis, their OD-matrix of trip distribution for 2019 is adopted as well.

The OD-matrix for 2019 was extrapolated to the prediction year of 2050 based on PTV Group (2023). They predict that the demand for long-distance travel will increase by 13% between 2019 and 2050. This results in the necessary input for the first step of the Combined Mode-Route Choice transport model.

It is worth highlighting that this 13% is relatively low. To provide context, Hilbers et al. (2020) estimated that average passenger kilometres per year will increase between 14% and 39% between 2018 and 2040, in either a scenario of low-economic growth or high-economic growth. The time range of Hilbers et al. (2020) is smaller than the time range of this research, yet both estimations are higher. The reason for still adopting the value of PTV Group (2023) is twofold. Firstly, PTV Group (2023) specifically concerns the context of long-distance travel, while Hilbers et al. (2020) concerns the total growth of passenger-kilometres per year. Secondly, in line with the previously discussed publication of Armstrong, Green, and Graefe (2015), the conservative estimation was preferred. This assumption is included in subsection 4.6.3.

4.4.2. Modal Split

Combining all the data gathered in this chapter into a combined mode-route choice model in accordance to chapter 3 has led to a modal split that is presented in Figure 4.15.

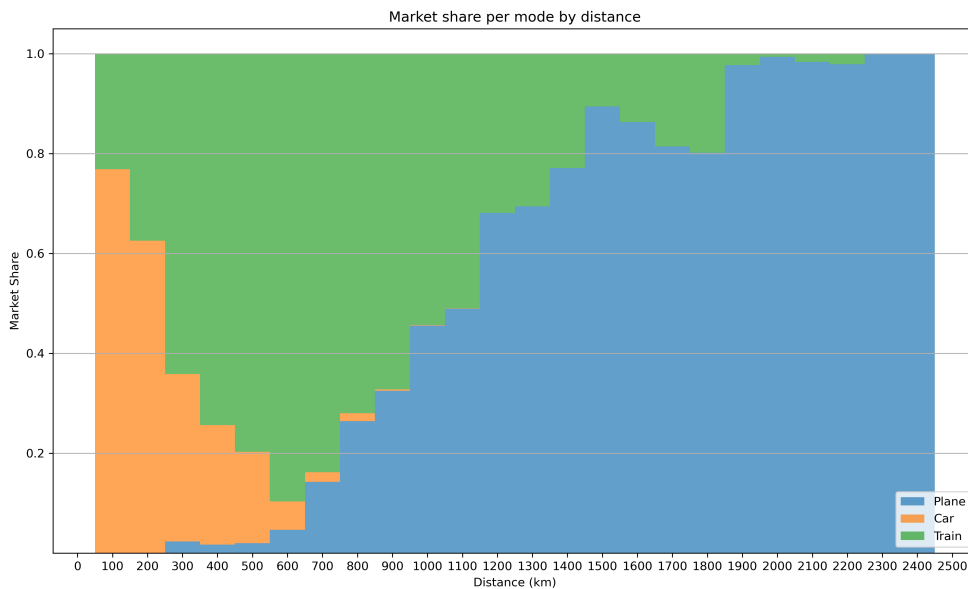


Figure 4.15: The forecast market share per mode over a range of long-distance trips for Europe 2050. Created in Python (Python Software Foundation, 2024).

The most applicable data with which this data was compared originates from Donners (2016), in the form of the previously shown in Figure 4.14. Figure 4.14 illustrates four scenarios for 2015 and 2030 that were modelled in Donners (2016), of which the 'Int.' for integration scenario 2030 is most comparable to the TEN-T Comprehensive Network that was modelled in this research, see Figure 4.5. When comparing this integration scenario with the result for 2050 of this research in Figure 4.15, the rail mode has substantially increased in performance. The plane and car, on the other hand, mode have decreased their share. This observation can be explained through two modelling choices. The first is that the railway network has significantly improved between the 2030 integration scenario of Donners (2016) and the modal split that is estimated for 2050. The integration scenario of Donners (2016) contains much fewer cross-border connections and none to little high-speed railways in the UK, eastern Europe and the Baltic states. Another argument that explains this gap is the inclusion of travel costs, which Donners (2016) did not do, and specifically the internalisation of carbon emissions. This does not impact the rail mode much, but it does reduce the attractiveness of the car and plane heavily.

No other visual modal splits from other research were found in literature for comparison, but the literature research of section 2.2 did entail a couple of statements on the competition between long-distance travel modes. An example of this is Wan et al. (2016), which states in the context of short-haul distances in China, i.e. less than 500km, that HSR dominates the airlines. Another paper, that applies a network model for the year 2020 in Western Europe, states that high-speed rail can compete with both European flights of up to 750 kilometres distance as well as with road transportation Adler, Pels, and Nash (2010). Figure 4.15 illustrates the potential of HSR in way that fits these statements, but assigns even higher market shares to rail. The hypothesis for this discrepancy is again, the inclusion of travel costs with a carbon internalisation policy.

Figure 4.15 shows remarkably high increases in the plane modal split that decrease the rail share at around 1100-1200 and around 1800-1900. These large increases can be explained by the transfer threshold approach of the rail utility section, as presented in Table 4.7, containing among others a threshold at 1189 and 1930.

Another notability concerns the relatively bad performance of car. This performance may match the integration scenario of Donners (2016) in Figure 4.14, but it is expected to be unlikely that the car will ever have zero market share from 1000 kilometres. To provide an example, the distance to the Alps or to the south of France is approximately this distance as seen from The Netherlands. Many people, at least in 2024, prefer to take the car due to its flexibility, space for bringing luggage, the possibility of bringing an own trailer or caravan, and in some cases, low travel costs due to the fact that the car is a lease that includes fuel costs. These considerations were not included in the model, that assumes that people are economically rational and decide purely on time and costs.

In conclusion, the modal split of Figure 4.15 seems logical in the context of the provided attributes and parameters in this chapter. Additionally, it is plausible that the modal split of 2050 will actually resemble this to a certain extent. Prerequisites for this resemblance are that the European railways will develop similar to the TEN-T European Commission (2021b) and that some, conservative, form of carbon pricing policy is implemented.

4.4.3. Route Assignment

The route assignment procedure was executed in accordance to the path size logit approach of chapter 3. Its results were as expected. This section contains an example that illustrates this statement.

The applied example in this section is that of the three routes between Antwerpen and Tampere, as they were visualised in Figure 4.8 in section 4.2. Path 1, the one generated with the aim of minimal in-vehicle time, has a path size factor (PSF) of 0.54. Path 2, the one generated for minimisation of the distance, has a path size factor of 0.68. Path 3, the one generated for the minimisation of disutility has a path size factor of 0.51.

If all three paths would have been identical, the path size factors would have equalled 0.33. If the PSFs had been 1, they would have been completely distinct. The provided values comply with this

theory. The value for path 2 is the highest, suggesting that it is relatively distinct. When analysing Figure 4.8, this is correct since Path 2 takes a relatively distinct route along the Baltic Sea. While Path 1 and 3 remain more inland and take (mostly) the HSR-path that will become the so-called Baltic corridor in the TEN-T network. Path 3 is the least distinct, which makes sense since it is based on disutility, meaning that its shortest path is a trade-off between travel time and travel cost. And since travel cost scales with distance, it is essentially a trade-off between in-vehicle time and distance. Path 3 is positioned geographically between Path 1 and 2, and shares most of its edges with them, therefore having the lowest Path Size Factor and being the least distinct.

In conclusion, the path size factor values seem consistent with theory. Applying the path size logit over the entire network generated a traffic distribution which is as expected, with high-passenger volumes on strategically located high-speed edges, and fewer to zero passengers on remote conventional railways. The result is presented at the end of next subsection and includes the induced demand effect.

Lastly, chapter 3 described a common issue with the PSL method, where unrealistic routes negatively impact the choice probabilities of realistic routes when links are shared. This issue is expected to be only moderately impactful since the three generated paths per station pair are specifically optimised for the attributes of the utility function or the overall utility, thus avoiding completely unrealistic paths in the model. While the model does not include unrealistic routes, it is anticipated that the shortest distance paths are less attractive in reality than they appear in the model. Services on these shortest distance paths often utilise links with conventional speeds. In addition, these paths are expected to be less integrated than routes that primarily use high-speed links, leading to more transfers during the the shortest-distance path trip. Since these shortest-distance paths are distinct compared to the other two paths and share few links with the alternatives, they have a limited impact on the path size factors and choice probabilities of the other two paths between stations.

4.4.4. Inclusion of Induced Demand Effect

A mode-specific multiplier was used to include the induced demand effect for the TEN-T railway edges that are constructed between 2019, the year from which the trip distribution data originates, and the prediction year of 2050. Figure 4.16 visualises which infrastructure this concerns. The described approach corresponds with the explicit recommendation of the literature synthesis in section 2.3 to include the induced demand effect in transport models, due to its potential of generating substantial passenger volumes.

The induced demand effect was specifically applied to rail since that is the only mode for which the infrastructure is assumed to improve between the reference year and prediction year of this research. Inclusion of this induced demand effect was also very desirable to accurately assess which HSR-stations might bottleneck in chapter 5. To estimate this rail-specific multiplier, a small literature review was conducted on the size of the effect of induced demand after construction of a (high-speed) railway.

Three different sources were found on estimation of the induced demand effect. These are the following:

- Preston (2009) concludes after a literature review of five HSR-introductions between 1987 and 2006, that induced demand is on average 26% of the total demand.
- Greengauge 21 (2009) has forecast that a full British HSR network would carry 178 million passengers in 2055. Of this total, 19% would be induced demand.
- Givoni and Dobruszkes (2013) conduct a literature review that contains passenger data from multiple ex-post rail projects. They conclude that, a few years after completion, the induced demand is usually 10-20% of the total demand, with outliers to 9% and 37%.



Figure 4.16: The visualisation of which TEN-T railways are planned to be constructed per 2050, and which are already existing. Based on the TEN-T policy (European Commission, 2021b) and created with QGIS (QGIS, 2023).

In conclusion; the review shows that the induced demand share for rail infrastructure is around the 20% after some years of operation. It is therefore assumed that passenger volumes on newly constructed TEN-T railways will also contain 20% induced demand. This means that the multiplier for induced demand is set at 1.25.

The transport model study of PTV Group (2023) was used for validation of the induced demand factor since it includes an induced demand effect in its future European network. PTV Group (2023) applies an induced demand share of 24% instead of 20%. This is relatively close to the result of the literature review above. The report of this consultancy firm does not clarify on what grounds it assumes 24%, so the 20% share was maintained for this research.

This induced demand factor was applied to the passenger flow to paths that contained newly constructed infrastructure. This approach was realised through scanning, per path in Python, for edges that had for the attribute 'STATUS' the entry 'New Construction'. NB: An edge might be defined as new construction if only a part of the edge is to be constructed prior to 2050. So not every 'New Construction' edge in the network of Figure 4.5, is completely novel in comparison to the base year.

Prior to applying this induced demand factor on the data, there were 488 million distributed long-distance rail passenger trips per year. Analysis of the network showed that 63.6% of these passenger trips take paths that contain new infrastructure. One could therefore conclude that the planned TEN-T railway edges are quite strategically planned. Application of the induced demand factor therefore generated an induced demand volume of 78 million, leading a new total of 563 million long-distance rail passengers per year.

The increase of 15% in total passenger distribution is substantial, but not out of the ordinary. Research

has shown that induced demand affects long-distance travel demand considerably and, by doing so, the economy. Evidence of long-distance induced demand effects on the economy can be found in Chen et al. (2016), which was previously discussed in the chapter 2. The paper provides ex-post estimations of the impact of HSR-investments on the economy and environment across China since the early 2000s, including a contribution of the induced demand volumes on the Chinese GDP. The authors suggest that induced demand as a result of HSR-investments have contributed 0.509% to the annual GDP, assuming *ceteris paribus*. This value is significantly positive and illustrates the potential effects of induced demand volumes.

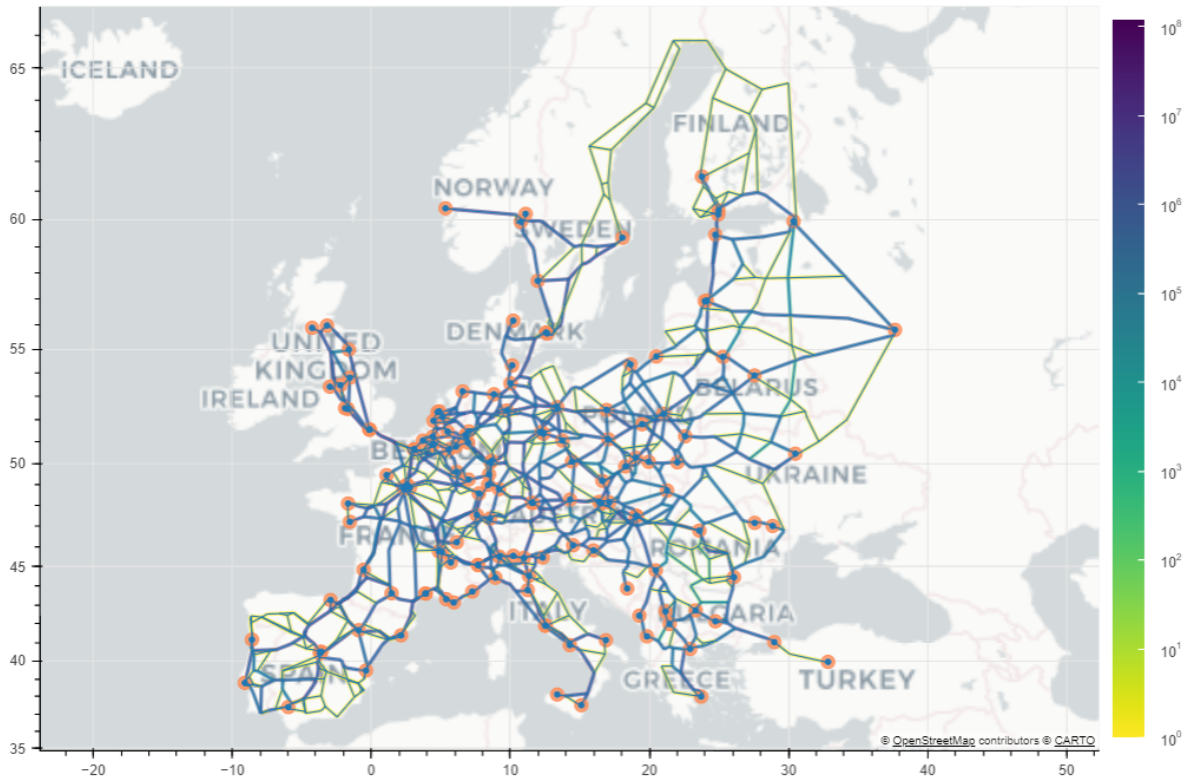


Figure 4.17: The visualised network assignment including induced demand volumes. The values that are aligned vertically along the logarithmic color bar represent the yearly passenger flows per railway edge. Modelled with NetworkX (NetworkX, 2023) and visualised with Bokeh (Bokeh Development Team, 2018) in Python 3 (Python Software Foundation, 2024).

4.5. Validation of the results

The transport model presented in this research, based on the TEN-T policy (European Commission, 2021b), generates a certain level of passenger traffic for the year of 2050. This section describes how this data was validated to confirm that the transport model accurately reflects reality.

Before describing the 'validation' process, it is important to establish that the validation data used in this section is not the ground truth. Forecast passenger volumes are always subject to many forms of uncertainty. No matter its source. Therefore, this section does not only discuss how the results of this research compare, but also tries to explain away the differences and similarities that lead to these results. 'Validation' was employed as the title of this subsection due to the absence of a more fitting term.

Validation requires data from a reliable source, for example from a respected institution or a scientific journal. The most obvious source for validation is the impact assessment that belongs to the TEN-T 2021 regulation (European Commission, 2021a), of which modelling specifics will be discussed later in this section. Ideally, it would contain link flows at an edge level like the passenger assignment in

this chapter. Unfortunately, predicted link flows for the Comprehensive TEN-T policy are not readily available, not in the impact assessment nor somewhere else. The impact assessment does however contain total predicted passenger-kilometers for the Comprehensive TEN-T policy, which could be compared with the results of the transport model created in this thesis.

The document by European Commission (2021a) assesses impacts for a baseline scenario and three policy options in which additional policies are proposed. The baseline scenario satisfies the TEN-T policy aims and represents, among others, the completion of the Core Network by 2030 and the Comprehensive Network by 2050. Since no additional policies were assumed in generating the results of this section, except for a carbon pricing policy which is comparable to the carbon pricing instrument that is present in the baseline scenario, the results of the baseline scenario will be used to validate the results of this section.

The authors of the impact assessment document retrieved the traffic volumes through use of a model called ASTRA (European Commission, 2021a). ASTRA is a strategic model that is based upon theory of Systems Dynamics Modelling. The model consists of multiple different models that can predict not only transport volumes, but also economic growth and environmental impacts of a policy. The similarities and differences between the ASTRA transport module and the applied transport model in this thesis are highlighted to accurately interpret the result. The main similarities include:

- ASTRA's procedure traffic estimation is similar. It estimates total passenger distribution values for 2050 and applies a modal split to assign these to the different long-distance modes.
- ASTRA includes both travel time and travel costs. The travel costs also include effects of the previously discussed ETS carbon pricing instrument, which has similar effects to the TMC policy that was applied in this research. Both have the objective of internalising the externalities of carbon emissions and will therefore increase air travel costs most, then car travel costs and then rail travel costs.
- The geographical scope is nearly completely similar to this research when it only concerns the HSR edges. ASTRA takes into account not only traffic within EU countries, but also from and to Norway, the UK and Switzerland. The only difference can be found in Turkey, which is a neighbouring country of this thesis' geographical scope. See Figure 1.2 in chapter 1.

There are however also differences between the two models. When comparing the full geographical scopes, the ASTRA model does not include numerous neighbouring (non-EU) countries that are included in this thesis' scope. Another difference is that the ASTRA model takes into account vehicle fleet, when assigning passengers to modes. While this thesis applies an unconstrained assignment, i.e. without the capacity limitations of vehicles. Overall, one could state that the ASTRA model is more comprehensive.

Quite some procedural similarities and differences have been described between this study's approach and ASTRA. Inputs have however not yet been described, the reason for this is that these were not findable. If they would have been, it would have been worthwhile to compare inputs like the Values of Times, choice parameters, and attributes. It is however known that ASTRA is calibrated with Eurostat data from 2000 to 2015.

The only metric from the impact assessment that can be applied is the total rail traffic volume in billions of passenger kilometres. The TEN-T policy (European Commission, 2021b) does however also contain the goal of tripling HSR-passenger traffic per 2050 in comparison to 2015, which can also be used as metric. Since the HSR passenger traffic was 110 billion passenger-km in 2015, including the UK who was a Member State at the time, the goal per 2050 is 330 billion pkm (European Commission, 2022). This value is also used to create a validation set of two different checks on rail passenger traffic results. An overview of these values can be found in Table 4.14.

The results of study, as shown in Table 4.14, are quite comparable with the validation data. The deviations can be explained partially by geographical scopes that do not completely align, but they can also be caused by diverting model inputs. As described before, it is however unknown to what extent these inputs compare. Overall, one can conclude that the results generated in this section of the thesis align quite well with the scarce validation data that is available. This suggests that the results of this study

Table 4.14: Validation of rail passenger traffic results in billion passenger kilometres.

Metric [Gpkm]	Thesis results	EU data	Validation source
Total rail traffic 2050	487	513	European Commission, 2021a
Total HSR traffic 2050	343	330	European Commission, 2022

are fairly realistic.

In addition to the validation data presented in Table 4.14, other sources were also consulted. Two consultancy reports were found that model different scenarios of the future European railways, namely PTV Group (2023) and EY (2023). Results of these two studies were, unfortunately, not directly comparable since they have not modelled the same European railway network as this study has, which is based on the TEN-T policy European Commission (2021b). PTV Group (2023) states that they do not expect the planned TEN-T infrastructure to be efficient in realising the EU objectives of tripling HSR passenger traffic per 2050. They substantiate this by presenting a predicted result for 2030 that does not match the EU's intermediate aim of doubling HSR traffic. This underestimation might be explained by the fact that PTV does not include carbon pricing instruments, which are taken into account in the impact assessment of European Commission (2021a) and this research.

4.6. Limitations of the transport model

4.6.1. Quasi-determinism

As mentioned in section 4.2 when discussing the determination of the transfer thresholds; the defined transport model is quasi-deterministic. The model's quasi-deterministic nature arises primarily from the use of Python sets to dynamically store urban areas during the path generation process. The inherent lack of order in which Python loops through sets leads to slight variations in results. This section first discusses how these variations can arise, then discusses the trade-offs that were made in selecting this quasi-deterministic code over a slower, deterministic and eventually how variations are prevented when having to compare different runs.

The randomness arises, as has been discussed, by a set that stores the urban areas along its path, defined as `urban_areas`. Python initially scans which urban areas are located along a generated shortest path and then adds them to the set. Then, within a while loop, the shortest path is diverted to include a station for every urban area that is found. It adds for every urban node the path that provides the local optimum between a start node and end node where between it searches. When two cities are located directly against each other, with their Functional Urban Areas touching each other, like Dusseldorf, Essen and Cologne, the order in which the shortest path detours are realised can influence the start and end edges where between it looks for a shortest path. It then matters which station is firstly processed and how the local shortest path is added. This is especially true when the order in which urban areas are processed may lead to the inclusion of a new urban area in one run, and not in the other run. This can happen because the while loop detects edges that contain any new urban areas after every urban detour generation.

The randomness that is caused by this process is negligible in the results of this transport model chapter, like the passenger assignment and the modal split, since the anomalies are quite rare. For example, in approximately 1 out of 100 cases, paths may differ by 1 to 2 minutes in in-vehicle time due to these processing order discrepancies. However, when comparing different runs to assess welfare effects of an infrastructure change, as will be done in chapter 6, this does form a problem. Fortunately, an approach was found that generates consistent results between runs while maintaining the appearance of sets.

An alternative to applying sets was to apply sorted lists. Sorted lists, instead of sets, can ensure deterministic results, but at a considerable cost in computation time. The deterministic approach, which involves sorting elements before processing them, ensured that the urban areas were handled in a consistent order across different runs. However, this method drastically increased path generation times

from 2-3 minutes to 10-12 minutes per run. Since every run of the transport model requires three shortest paths, this would make the total running time 30+ minutes, which is infeasible for the number of iterations in chapter 6. Another argument for not adopting the deterministic approach is that the quality of the generated paths does not necessarily improve with determinism; it simply ensures consistency. The quasi-deterministic approach, while less consistent, was therefore chosen for its time-efficiency. As noted by Sam McKay (2023), sets offer much faster search times compared to lists, making them more efficient for this application.

To work with the quasi-deterministic nature of the model, certain precautions had to be taken. It is crucial to maintain the same kernel and seed to get consistent results across multiple runs of the same single Python process. The randomness introduced by sets can be controlled by setting the Python hash seed environment variable, which stabilises results within the same process. However, this consistency does not extend across different invocations of Python (Python Software Foundation, 2024). Thus, ensuring reproducibility requires careful management of the computing environment. It may not go to sleep, nor shut down. The approach outlined in the introduction of this thesis' code recommends to set the hash seed at the start and not to alter it between runs, thereby maintaining consistency as long as the kernel is not restarted. This allows for comparing results of different runs.

4.6.2. NetworkX limitations

As has been discussed in the chapter 3, NetworkX is a valuable, but limited model. You can not add additional constraints to shortest paths function, but for adding weights. This severely complicated the alterations to include stops at one station per area. Another limitation is that it does not allow for multi-labeling approaches, which is why the labelling approach was executed. In addition, NetworkX is not very time-efficient in finding the k-shortest paths in a large network like the one applied in this study.

Since NetworkX includes only the possibility of applying the shortest path labelling approach Fiorenza-Catalano, Van Nes, and Bovy (2004), no extra constraints or objectives were provided to the path generation. If this would have been an option, it would have been good practice to limit the number of switches from HSR to conventional rail. Currently, this model allows for paths that constantly switch from HSR service to conventional service and vice versa, as long as this provides the shortest possible path for the selected weight. This decreases realism, which is why you would preferably limit the number of switches in the path generation.

4.6.3. Overview of Assumptions

This study has made many assumptions, mainly in this chapter, both to scope the research and to ensure that the model was feasible. Many of them are small and have limited influence, while others are very influential in the establishment of the results. All assumptions that were regarded as potentially influential have been included in this section.

This subsection discusses these assumptions separately, including their potential impacts on the results and the likelihood that the assumption is an oversimplification of reality. The assumptions are discussed, approximately, in the order in which they apply throughout the study. They are labelled A1, A2 et cetera, with A standing for assumption.

After the discussion, the assumptions are listed in a table that specifies both the expected impact of the assumption and the likelihood that the assumption oversimplifies reality, i.e. the likelihood that the impacts will occur. Models exist to mimic reality, and the modelling assumptions aim to contribute to this. These assumptions can however also oversimplify reality, the likelihood that this is the case is described per assumption in this section. If the likelihood is low, the assumption is expected to reflect reality relatively well. If the likelihood is high, it is known with high certainty that the assumption oversimplifies reality. An example of the latter is the assumption that choice parameters apply equally to all types of passengers, while it is illustrated in literature that business and leisure passengers have substantially different parameters (Lee, Yoo, and Song, 2016).

- A1. The selection of the 124 origins and destinations, and the corresponding passenger distribution matrix of Grolle et al. (2024), effectively makes this model a city-trip transport model between the

commuting zones (FUA) of every city. The selected cities only contain about 40% of Europe's total population (Donners, 2016), although the passenger distribution matrix is based on air passenger trips (Grolle et al., 2024) and does therefore not originate from the inhabitants per city. The definition of the FUA as the catchment area for stations is, however, expected to be an impactful limitation, leading to an underestimation of the access/egress times. Literature states that the catchment areas of HSR-stations typically have a radius of about 25-30 km (Marti-Henneberg, 2015), which matches the average size of a FUA. However, people from rural areas might just as well decide that they wish to travel long distances by train. Taking these people into account would increase the average access/egress times for rail, leading to a lower market share than currently estimated.

- A2. The geographical design of railway corridors as mapped in the TEN-T policy (European Commission, 2021b) is assumed as the future reality. A consequence of this is that some future TEN-T lines were modelled unrealistically straight, not keeping into account urban or natural obstructions. The cause of these straight lines is a lack of geographical design, which is yet to be made. They only reflect that the urban nodes will be connected through a railway and where this railway will approximately be. Examples of such railways are the new HSR line through the centre of France, located between the south side of Paris and the west side of Lyon, and some high-speed railways in Hungary and Poland. The impact of this assumption is limited due to the low-frequency of this phenomenon. It does lead to some overestimation of the rail mode.
- A3. This thesis assumes that the EU and its Member States will realise the 2050 European railway network exactly as envisioned in European Commission (2021b). While in reality, its realisation is subject to (political) willingness at all governmental levels. Ambitions might change with every election, both in a more ambitious and less ambitious direction. It is therefore very unlikely that the proposed Comprehensive TEN-T policy plan, that is assumed in this study, will be realised between 2024 and 2050 exactly in the way in which it is envisioned. The policy regulation itself was, for example, renewed after eight years (European Commission, 2013; European Commission, 2021b), with the UK leaving the Union in the meanwhile. In addition, the TEN-T maps have proposed only a macro-level design. Countries, and more local authorities, make the final decisions, which do not always align with the TEN-T. For example, the online interactive TEN-T map European Union Agency for Railways (2022) does not suggest that the HSR-network will include a stop at the airport of Stuttgart, while an underground tunnel between the Hauptbahnhof and airport station is in reality already under construction (Matheisen et al., 2024). In conclusion, it is inevitable that changes to the envisioned TEN-T policy will occur within the EU, but its impact on the passenger welfare conclusions of this thesis are expected to be low.
- A4. This thesis also assumes that non-EU states will cooperate in the creation of the European network as envisioned in European Commission (2021b), specifically for the realisation of the railway infrastructure in the neighbouring countries of Figure 1.2. In some cases, this assumption is likely to reflect reality. The EU has, for example, good relations with the UK, Norway, and Switzerland. However, cooperation to create a unified European network is less likely on the eastern border of the EU, especially given the current war in Ukraine due to the invasion of Russia. In addition, China is also involved with European high-speed rail, having financed elements of the construction of a high-speed railway between Belgrade and Budapest (RailwayPro, 2022). This new railway, planned to be opened in 2025, is an example of a railway that is not included in the TEN-T policy (European Commission, 2021b). The impact of assumption A4 on the results is also expected to be low, since most of the demand of the passenger distribution matrix is located in central and western Europe. The likelihood that impacts will occur, and thus that the network will not develop as planned in the neighbouring countries, is however expected to be high.
- A5. It has been assumed that the road and air modes do not change in infrastructure and services up until 2050. This *ceteris paribus* assumption is a limitation of reality for different reasons. Roads will also develop in accordance with the TEN-T policy (European Commission, 2021b), albeit much less than the rail network. These new roads would in addition also draw induced demand, just like rail. The plane services between OD-pairs in the network will definitely also change, but no predictions can be made on that behalf. It is expected that this assumption leads to moderate overestimation of the rail mode.
- A6. A major assumption of the station selection procedure was to select, in most cases, only one station per city. This does not impact the results much from a service perspective, since European

long-distance trains commonly visit only the primary railway stations of a city (Kellerman, 2012). It does, however, impact the average access/egress time. If the model allowed for selecting multiple stations per urban node that all provide long-distance services, this would decrease the average access/egress time for such a long-distance trip. Passengers would then be able to choose the station which is closest to them and then travel to the departure station of their high-speed rail journey. An example of such a station that does provide high-speed rail services, but is not included in the selection, is Berlin Spandau (Matheisen et al., 2024).

- A7. This model implicitly assumes that all passengers have a car that they could select as their long-distance mode of choice, while in reality the number of cars per inhabitant is 0.57 (Eurostat, 2023). The estimated impact on the results is medium, since the car already has the smallest share in the modal split.
- A8. This model provides passengers with three path options between destinations, assuming effective regular service between all OD-pairs, albeit with transfers. This assumption is a relatively impactful one, with reality being unruly. Numerous examples exist of HSR-stations that have weak services (Moyano and Dobruszkes, 2017). In addition, European Court of Auditors (2018a) state services as third in impactful indicators of HSR success, directly after travel time and price. Weak or inconsistent services on the long-distance rail network would decrease the attractiveness of the rail mode. The chance that such service issues arise on a large scale is deemed medium.
- A9. One of the objectives of the European Commission (2021b) is to create a network with 'multimodal transport solutions' that make the transport sector greener, more efficient and more resilient. In addition, European Court of Auditors (2018a) state that: 'High-speed rail and air can be complementary. By delivering passengers to an airport, high-speed rail can enlarge the airport's catchment area, and air passengers may decide to use a given airport because of a seamless and fast rail connection after landing.' This potential is also recognised by Voltes-Dorta and Becker (2018), who expects that HSR-connectivity can assist in enable major airports to attract air-rail transfer travelers from the catchment areas of smaller airports. In contrast to these goals of the EU, multi-modality has been excluded from this study. This was done since it currently does not occur often Donners (2016), and it is also one of the main concerns of the TEN-T policy (European Commission, 2021a). In addition, it was also excluded from the model to decrease the complexity of the model. The impact of its exclusion might be considerable, especially since HSR might perform as an excellent access/egress mode to airports. This thesis, for example, assumes that people are willing to consider airports that are located up to a 2.5-hour car ride away from their city, which very much allows for the option of high-speed rail to reach that airport. The likelihood that multi-modality will play a substantial role per 2050 is estimated to be moderate.
- A10. The assumption has been made that waiting time for initiating a long-distance rail travel is on average 15 minutes. One of the main potential causes for waiting times to be longer than 15 minutes is when people would incorporate waiting times at customs control in their time of arrival. However, customs checks are not required for Europeans traveling within the Schengen area, which encompasses most of the study area. Specifically, 24 countries within the scope are part of Schengen, including 95 out of the 124 chosen urban nodes. Given that most of the passenger distribution is within the Schengen area, the anticipated impact is considered to be low.
- A11. The inter-station transfer speed for London, Paris, and Budapest is assumed to be 19 km/h, which was based on the estimated urban access/egress speed for railway stations. Examples do however exist which suggest that the transit speed might be higher. Paris, for example, has a transit line between Gare de Nord and Gare de Lyon which takes only 7 minutes and travels 5.5 kilometres. While in Budapest all of the three main stations are connected through the metro system (Austrian High-Speed Trains, 2024). On the other hand, it has to be taken into account that this 19 km/h also contains transfer times between modes. It is therefore assumed that this speed is fairly realistic and has a low impact on the results. Especially since this only concerns 3 cities out of the 124.
- A12. This chapter assumes that passengers dislike transfer times 1.5 times more than in-vehicle time, but it does not include a general dislike of transfers. Such a transfer penalty is however common in literature (Nielsen et al., 2021). The study by Nielsen et al. (2021) notes that it is widely recognised that a transfer within a public transport system not only increases the disutility of the journey in proportion to the time spent on the transfer, but also imposes a constant disutility for each

additional transfer during the trip. This disutility is among others caused by discomfort and the risk of missing a connection. Nielsen et al. (2021) state that transfer penalty constants in general represent about 5 to 20 min of additional in-vehicle time. One can conclude that the exclusion of a general transfer penalty has led to an overestimation of the rail mode, especially at longer distances where more transfers are assumed.

- A13. This study assumes that peripheral stations have an average access/egress of 27 km/h, while central and urban stations have an average access/egress of 19 km/h. This approach is coarse and leads to an overestimation of the attractiveness of peripheral stations that are located very close to the urban centre. An example of this is the peripheral HSR-station of Copenhagen As-trup Airport (access/egress time of 0.83 hour), which is more attractive than its central counterpart of Copenhagen Hovedbanegård (access/egress time of 0.89 hour). This is caused by the fact Astrup station is located just outside the border of the urban centre (OECD, 2023), but has a population density of <300. It was for this reason identified as a peripheral station (United Nations Statistical Commission, 2020), and assigned with an access/egress speed of 27 km/h. This assumed overestimation of attractiveness of peripheral stations that are close to the urban centre is assumed to be impactful in both the passenger assignment and the bottleneck identification, but even more so in the estimation of passenger welfare effects. The described situation of Copenhagen occurs multiple times in the station set, e.g. in Frankfurt Am Main and Montpellier, it was therefore expected to occur in some of the passenger welfare experiments of chapter 6 as well.
- A14. It has been assumed that train tickets for HSR are equally expensive as those for conventional trains. This assumption is estimated to be moderately impactful, decreasing realism of the model. The French HSR (TGV) is more expensive in comparison than its conventional counterpart, and literature states that this is in general the case when comparing HSR with conventional rail (European Commission, 2016). Since the travel costs occur from Tanner (2023), who gathered them for 2022 through web-scraping of long-distance rail, it is expected that most of the costs concern HSR. This suggests that the costs for travel on conventional railway edges have been modelled at a too high value, leading to an underestimation of passenger flows on the conventional railways and an overestimation of passenger flows on the high-speed railways.
- A15. The assumption that access/egress trips do not incur travel costs, while the main long-distance modes do, creates a discrepancy in the way these modes are treated in the utility function. Including access/egress costs would have enhanced the realism of this model. This change would effectively result in both plane and train modes performing worse in the modal split, as those trips would then include two downsides, whereas car trips, which do not involve an access/egress element, would perform better. It is expected that this assumption has a substantial impact in the results of the passenger welfare experiments of chapter 6. The likelihood that this assumption is an oversimplification is set at high since access/egress trips generally have a travel cost, with the exception of Luxembourg.
- A16. It is assumed that a carbon internalisation instrument will be introduced, aligning with recent EU policies and their corresponding impact assessments (European Commission, 2021b; European Commission, 2021a). The concept originates from a political background that is progressive on climate action, making it sensitive to future political currents. The impact of this assumption is high and particularly influential to the modal split. Nevertheless, the likelihood that this assumption will not correspond to future reality is low, given its firm establishment in multiple EU policies.
- A17. The implementation of a carbon internalisation policy is considered likely. However, the implementation of a Tradable Mobility Credit system, as applied in this thesis, is much less probable (Tanner, 2023). The impact of applying this policy concept, instead of the Emission Trading System policy (European Commission, 2021a), is expected to be limited since both aim to achieve similar goals. Although they may operate differently, both policies would eventually lead to higher prices for aeroplane tickets, relatively higher pricing for car tickets, and only slightly higher pricing for rail tickets, which is precisely what has been modelled in this section. In conclusion, the likelihood that TMC will not be the implemented carbon policy is high, but the corresponding impact is moderate.
- A18. The rail transfer subsection section assumes that the number of rail transfers scales with the travelled distance. In other words, rail passenger have to take transfers at certain thresholds, with the first transfer occurring at 527 km. This is effectively an estimated average, but it might

very well be too low. It is, for example, already possible to travel from Amsterdam to Berlin without having to transfer, which is a bit longer than 527 km (Google Inc., 2024). On the other hand, 527 might also be an overestimation, since travelling from Rotterdam to Köln does require a transfer, which is less than 527 km. In conclusion, there is no evident reason to doubt that this average is far from the truth.

- A19. Table 4.11 assumes that both access and egress have a travel time weight of 1.36 compared to the in-vehicle time. However, Zhen, Cao, and Tang (2018) concluded in their research that egress has a larger influence than access. Incorporating this difference in the model would have resulted in some strategically located stations becoming egress-focused stations due to the greater distaste for egress, while less strategically placed stations could have become access-focused stations. This could have led to an unrealistic discrepancy between arriving and departing rail passengers, complicating vehicle allocation. Although excluding the difference in taste for access and egress reduces realism, it has been practical for this study.
- A20. It is important to note that the assumed autonomous growth rate of 13% is relatively low. For context, Hilbers et al. (2020) predict that average annual passenger kilometers will increase by 14% to 39% between 2018 and 2040, depending on whether economic growth is low or high. Although Hilbers et al. (2020) cover a shorter time span than this study, their projections are still higher. Their values do, however, not specifically concern long-distance travel. In conclusion, there is a possibility that the passenger distribution results are underestimated. This underestimation would mean that fewer bottleneck stations are identified in chapter 5 and that the passenger welfare effects of chapter 6 are also likely to be underestimated.
- A21. It has been illustrated by (Lee, Yoo, and Song, 2016) that travel attitude characteristics are very different for business and leisure passengers, but for the sake of the scope no division between the two was made in this research. Instead, a Europe-wide Value of Time was estimated by taking the average of the Values of Time for both business and leisure passengers (Wardman et al., 2012).
- A22. It has been assumed that the Value of Time is, on average, €25 in 2024 and will be €39 in 2050. Taking an average GDP for an entire continent is a strong assumption, especially since these values vary significantly by country (Wardman et al., 2012), and GDP trends also differ considerably per country (Eurostat, 2024). As a result of this assumption, regional differences are not accounted for in the transport estimations, while they do exist. For example, passengers in stronger economies might choose to fly more often, as air travel is predicted to be the most expensive mode per kilometer in 2050, while passengers in smaller economies might opt for the train more frequently.
- A23. This study assumes that choice parameters are consistent across all modes. Literature has, however, identified that the satisfaction of passengers can also be influenced by the mode itself. Zhen, Cao, and Tang (2018) have put this forward in the context of access/egress modes, but it can also apply in the context of the main mode choice. The exclusion of such mode-specific preferences can be substantial, but it is uncertain whether and in what distribution they exist in Europe.
- A24. The distribution of long-distance passengers as assumed in this study, based on Grolle et al., 2024, knows its limitations. The passenger distribution dataset originates from air travel passenger data with flight legs that were at minimum 200km. For this reason, this research assumes 200 km to be the minimum distance of a long-distance trip, while other researches like Donners (2016) have assumed a minimum of 100 km in the definition of a long-distance trip. This leads to an underestimation of 'short' long-distance trips. In addition, this exclusion of short long distance trips is expected to unrealistically influence the trade-off of passenger welfare effects when testing the peripheral HSR-station experiments in chapter 6. Especially since an increase of access/egress time, a consequence of relocating HSR-service to city outskirts, is a relatively impactful when taking a 'short' long-distance trip. An example of this was provided in the literature analysis, where rail passengers between Brno and Prague (180 km) were strongly opposed of relocating the Brno Main Station away from the city centre (Kowalski, Marada, and Chmelík, 2023).
- A25. This study assumes that the mode choice behaviour of long-distance travellers is accurately represented by the path size logit (PSL) method. PSL assumes that people dislike correlations between alternatives and penalises routes that share much of their path with other routes. Although

no specific research on the applicability of PSL in long-distance travel was found, research in the context of public transport (PT) did provide insight (Dixit et al., 2023). The study by Dixit et al. (2023) indicates that overlap among paths behaves differently in PT than PSL assumes. Specifically, while subsequent overlap of journey legs is valued negatively, the overlap of transfer nodes is valued positively by travellers, especially when multiple distinct travel options are available at common transfer locations. In other words, PT passengers do not inherently dislike all overlaps, as PSL assumes, although they do dislike overlap of subsequent legs. If this finding also applies to long-distance travel, then the PSL method used in this study has a substantial shortcoming. Incorporating the preference for common transfer locations would result in higher estimated market shares for paths that include these stations. Generally, this would mean that the minimised-time path and minimised-disutility path would likely have a higher market share, as these are typically less distinct than the minimised-distance path. An example of a situation in which common transfer nodes are shared between these two types of paths was provided in Figure 4.8. This redistribution, due to the preference for main transfer locations, would lead to an increase in passenger flows at high-speed stations. This could lead to more bottlenecks stations, since traffic flows would be more aggregated, and higher passenger welfare effects when these stations are relocated. The likelihood that PSL inaccurately simplifies reality is, however, uncertain. The rationale for this is that the research by Dixit et al. (2023) focuses specifically on PT and not on long-distance travel.

Table 4.15 provides an overview of the assumptions as labelled above. It also contains the estimated impacts of the assumptions and the likeliness that the assumptions simplify reality too much. Both are provided in a classification of either low, medium or high.

Table 4.15: Overview of assumptions of the transport model.

ID	Assumption	Impact of assumption	Likelihood of oversimplification
A1	The catchment area per station is equal to the area of the corresponding urban node (FUA).	Medium	Medium
A2	The macro-level design of the TEN-T rail network reflects the actual future of the European rail network.	Medium	High
A3	The EU and its Member States will realise the 2050 European railway network, as envisioned in TEN-T.	Low	High
A4	Non-EU states will cooperate in the creation of the 2050 European network, as envisioned in TEN-T.	Low	High
A5	No changes will occur in the infrastructure nor services of the rail and air mode up until 2050.	Medium	High
A6	Most cities contain only one station for long-distance rail travel.	Medium	Medium
A7	All long-distance travellers have access to a car that they can select as their mode of choice.	Medium	High
A8	Frequent rail services will be available between all OD-pairs in 2050, albeit with transfers.	Medium	Medium
A9	Multi-modality will not play a role in long-distance travel.	Medium	Medium
A10	The waiting time for initiating long-distance rail trips is on average 15 minutes.	Low	High
A11	The transfer speed between urban stations is 19 km/h.	Low	Medium
A12	Transfers are only penalised in proportion to the transfer time. No constant transfer penalties are included.	Medium	High
A13	The average access/egress speed is 19 km/h for urban stations, while it is 27 km/h for peripheral stations.	High	High
A14	Train tickets for high-speed trains are equally expensive as those for conventional trains.	High	High
A15	Access/egress trips do not have travel costs, while the main long-distance modes do have travel costs.	High	High
A16	A carbon pricing instrument will be implemented.	High	Low
A17	The carbon pricing instrument that will be implemented is the Tradable Mobility Credit system, instead of the Emission Trading System.	Medium	High
A18	The number of transfers during a rail trip is proportionate with the travelled distance.	Medium	Low
A19	Both access and egress have a travel time weight of 1.36 compared to in-vehicle time.	Medium	Medium
A20	The total autonomous growth rate for long-distance travel in Europe between 2019 and 2050 is 13%.	High	Medium
A21	There is no division between choice behaviour of business and leisure passengers.	Medium	High
A22	The European Value of Time is on average €25 in 2024 and will be €39 in 2050.	Medium	High
A23	Choice parameters are consistent across all modes.	Medium	Medium
A24	Long-distance trips are defined as trips from 200 km.	High	Medium
A25	The mode choice behaviour of long-distance travellers is reflected by the path size logit (PSL) method.	Medium	Medium

5

HSR-Stations as Bottlenecks

This chapter estimates which centrally-located high-speed railway stations are at risk of being oversaturated per 2050. In other words, it quantifies which stations will experience a demand that exceeds the capacity. In doing so, this chapter provides an answer to the first research question (Q1) while simultaneously providing input that scopes the passenger welfare analysis of chapter 6.

5.1. Selection of HSR-stations

This research entails estimating the saturation levels of centrally-located HSR-stations and relocating services for these bottlenecks. The arguments for restricting the scope to relocating services from centrally-located HSR-stations to peripherally located HSR-stations are provided in chapter 1. The selection of stations for this chapter follows from that reasoning.

The definition of a central area has been provided in the list of key definitions in section 1.7 and does not require further elaboration. In addition, the definitions list also contains definitions for urban and peripheral areas. Figure 5.1 visualises which stations are central, which are defined as urban and which are peripheral.

The selection of HSR-stations was initially generated by visual inspection of the previously defined TEN-T network map generated in Figure 4.5. The HSR-station selection process applied a constraint to make sure that the stations in this bottleneck analysis selection could also lead to welfare benefits. This constraint is the following: HSR-stations are only included in this bottleneck analysis if the high-speed railway line maintains its average speed of 215 km/h up to the GHS urban core (Schiavina et al., 2019), which is the area in which it is assumed that the average train speed is 130 km/h. This constraint was set since passenger welfare benefits are only expected to occur if a high-speed train maintains its speed at least up until the city core, therefore potentially benefiting of relocation and being able to maintain its high speed for a longer of time. This additional constraint removes two extra stations from the equation, being Basel and Zurich. The high-speed trains that make halt at these stations decrease their speed relatively far away from the urban core, according to the maps of (European Commission, 2021b) which is the applied policy scope.

Filtering the station set to include only centrally-located HSR-stations creates the station selection for this chapter. This selection contains 95 of the 154 stations in the total set of stations.



Figure 5.1: Identification of centrally-located stations.
National borders are adapted from Eurostat (2020a) data. Created with QGIS (2023).



Figure 5.2: Identification of HSR-stations.
National borders are adapted from Eurostat (2020a) data. Created with QGIS (2023).

5.2. Long-Distance Passenger Traffic

To estimate the saturation levels of the selected stations, both demand and capacity are required. The approach of applying these variables was presented in the formulae in section 3.3. This subsection quantifies, with the use of the results of section 4.4 and parameters from literature, the estimated long-distance passenger train demand per station in 2050 in accordance to equation 3.15.

The first variable estimated for the saturation analysis, LD_{Pass} , is defined as the sum of OD- and traversing long-distance passengers per day at station s . This variable is computed in Python by using the resulting path flows of section 4.4, which include the induced demand passengers, and assigning it to the selected station nodes in the NetworkX graph. The result of this is that every centrally-located HSR station node contains this data in Python. The following is an example of the result that one retrieves when executing 'G.nodes[956]' in the base-model code:

```
'lat': 43.77673147326863,
'lon': 11.247903000429966,
'is_station': True,
'AREA': 'Florence',
'fid': 102,
'ACC_TIME': 0.486,
'NAME': 'Firenze Santa Maria Novella',
'origin/termin': 8193807,
'traverse': 36335108,
'total_p': 44528915
```

The 'total_p' value represents the total number of individual passengers that are estimated to travel from, to or through a station, in this case Firenze Santa Maria Novella in Florence. Hence, providing the LD_{Pass} .

The other two variables that were necessary for the quantification of Equation 3.15 were $Seat_{Cap}$, the (seat) capacity of passengers per train, and the Occ_{Rate} , which is the occupancy rate per train. Both of these values were based upon literature.

The seating capacity per train is assumed to be 350 seats based on the research of Grolle et al. (2024), which takes a relatively conservative estimate on the capacity analysis of Campos and de Rus (2009). This paper focuses solely on high-speed trains, which tend to have a capacity higher than 350, but this research also includes conventional trains in its definition of the train mode, that tend to have lower capacities Donners (2016). For this reason the 350 seats are assumed to be applicable for this research.

There is however an additional phenomenon that has to be taken into account when defining the seat capacity, being the coupling of trains (Soliman et al., 2019). In Europe, trains are increasingly physically coupled by using a coupler between the noses of two trains (Deutsche Bahn, 2024a; International Railway Journal, 2024). A railway operator which operates relatively many coupled trains is TGV (Laroche, 2014). Application of couplers can theoretically double the capacity of train and therefore that of a railway platform, if the platform is long enough. Laroche (2014) state that a double train rate of 1.3 occurred between Paris and Lyon. Given that France leads in the use of these couplers for high-speed trains, and considering that this trend is specific to HSR, while this research model also includes conventional rail, the average double train rate across Europe is conservatively estimated at 1.2. This assumption is in line with the scientific publication of Armstrong, Green, and Graefe (2015) called 'Golden Rule of Forecasting: Be conservative'. Applying this value of 1.2 leads to an average seating capacity of 420.

This section is finalised by assuming an average load factor, which is again done with the use of Laroche (2014). The authors state that the load factor of the TGV was on average 80% in 2008 between Paris and Lyon. This value is assumed to be applicable on the entire 2050 European rail network.

5.3. Commuter Train Traffic

To determine the total train traffic demand for the 95 stations by 2050, data was required on both long-distance trains and commuter trains. As this study concentrates on long-distance travel, data on commuter trains has not been gathered or mentioned in this report. Consequently, external sources were used to acquire this information. The results of this chapter can be found in Appendix C.

5.3.1. Data Acquisition of Train Traffic Per Station

In order to quantify Com_Demand_s and facilitate the application of ??, it was essential to estimate these values using publicly available data on train traffic near stations. A difficulty arose; extensive desk research did not provide a complete dataset containing train traffic for the 94 stations, let alone commuter train traffic data.

The 'Train Traffic on the Rail Network' folder from Eurostat (2024) provided a solution. The dataset includes traffic volumes for each rail link by country, encompassing links close to stations, though the granularity differs by country and year. In addition, there is no distinction between commuter/regional trains and long-distance trains in the database. Therefore, the proportion of commuter trains in this set is estimated in a different way, which is explained in subsection 5.3.2.

Retrieving the total demand for train traffic per station via Eurostat (2024) was labour intensive. The applied process is illustrated below using Linz Hauptbahnhof (Hbf) as an example:

1. In the database, one can choose traffic data sets by country and year, with the most recent choices being 2010, 2015, and 2020. Through investigation, it became clear that 2020 generally offered the most detailed and easily interpretable results. The 2020 folder, however, lacks data for some countries where the 95 stations are situated. Consequently, the available data and its usability for each country were reviewed in advance. If the 2020 data was either unusable or missing, the data folders from 2015 or even 2010 were also examined. For Linz, the dataset "Train Traffic on the Rail Network - Austria (2020)" was selected, simply because no data exists for Austria from previous years. This inconsistency in data availability and format is due to the varying levels of detail provided by Member States to the Eurostat database, if they provide any data at all.
2. After selecting the dataset, the 'Train Category' was set to 'Passenger Trains'. This step excluded the freight traffic from the data.
3. Next, the relevant railway network segments that determine how much traffic goes through a station must be selected. This can usually be done by searching for the station's name, but in some cases, the station name is not in the dataset. In such cases, OpenRailwayMap was used to analyse which railway junctions are located around the city (Matheisen et al., 2024). An example is Cluj Napoca in the 2020 dataset of Romania, which requires using the railway segment from Ciucea - Apahida and vice versa. For Linz Hbf, eight railway segments were found by searching for Linz Hbf. These eight segments were effectively four segments in both directions. To prevent double-counting trains, the approach was to sum the departures at each station. The underlying theory is that every departing train must have arrived at some point and used a platform. Figure 5.3 shows the resulting selection.
4. Every selection of railway segments was then verified with the names of surrounding railway stations and railway junctions in OpenRailwayMap (Matheisen et al., 2024). If that software did not provide the necessary names for validation, Google Maps was consulted (Google Inc., 2024). The four destination names from Linz Hbf, being Wels, Kirchdorf, Pregarten, and St. Valentin, were validated with a combination of the two geographic tools. Figure 5.4 shows all of these destinations in the surrounding area of Linz Hbf, with only Kirchdorf being located further to the south via a different railway segment.
5. The train traffic data was computed to find the total train traffic demand per year. This data was saved along with the reference year of that specific dataset to correctly apply the growth to 2050 in a later phase. The result for Linz Hbf was 89,100 trains per year.

↕ ⌂	TRAIN	Passenger trains ↕
NET_SEG20 ↕		
Linz Hbf (In Lz) - Wels Hbf		35 640
Linz Hbf (In Lz) - Pregarten		9 360
Linz Hbf (In Lz) - Kirchdorf A.D.Krems		12 780
Linz Hbf (In Lz) - St.Valentin (In Sv)		31 320

Figure 5.3: Screenshot of the Eurostat (2024) database.

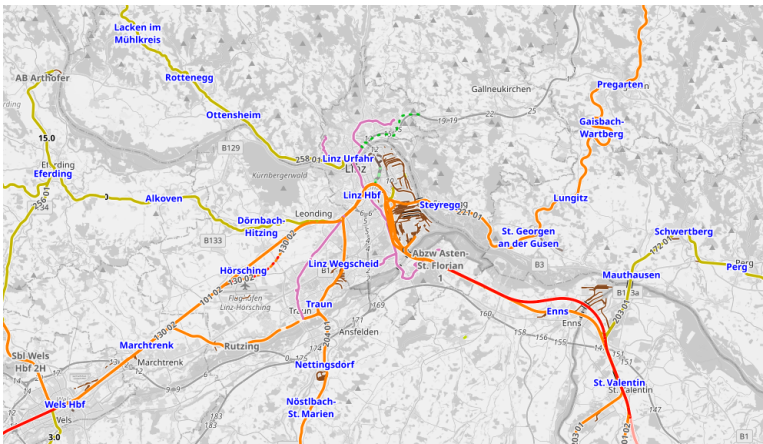


Figure 5.4: Screenshot of the OpenRailwayMap database (Matheisen et al., 2024).

A remark should be added to step 1 of the procedure list. The selection of the year 2020 was frequently chosen, which might appear unreasonable since 2020 was the year that the COVID-19 pandemic struck Europe, resulting in passenger-kilometers being 46% lower than normal (European Commission, 2023). The decline was mainly on the demand side, as people preferred more individual modes of transport. The supply side, however, was five times less affected, with an 8% decrease (IRG Rail, 2021). Only some train operators cancelled their train services (European Commission, 2023). Although the reduction on the supply side is substantial, it does not render the 2020 data unusable. In fact, the data from 2020 was selected most, as can be seen in Appendix C, despite the 8% abnormality in the data due to COVID-19. The reason for this is that it often contained the most detailed and readable data, as has been mentioned in bullet 1 of the procedure.

Another remark that must be made is that only the traffic at station tracks is computed that might be of use to high-speed trains. This point is made because the Eurostat dataset includes traffic data for railway elements that are unsuitable for long-distance travel. For instance, S-Bahn platform tracks are typically built in a separate departure hall, often located below the existing conventional and high-speed train platforms. These 'tief' platforms, meaning deep platforms, are designated for S-Bahn and are not suitable for long-distance train capacity, hence they are excluded. S-Bahn refers to a local urban rail system found in German-speaking cities (Eurostat, 2024).

This described procedure was applied manually to the entire station selection set. The Eurostat (2024) did not provide processable data for every station, so in some cases an external source was used. This is mostly the case for Polish and French stations, which had either too finely meshed data or not enough data, making it hard to realistically compute the total traffic per station. The applied source is included per commuter train estimate in Appendix C.

The one exception when it comes to the completeness of the traffic data in Appendix C is the to-be realised Birmingham Curzon Street (BBC, 2018). This station is part of one of the three regional policy plans that were included next to the TEN-T policy in section 1.7. Since it is not yet realised, there are currently no traffic volumes. This is not impactful for the saturation analysis since it is assumed that this new station is designed to have sufficient capacity for the future.

5.3.2. Commuter Train Traffic Per 2024

An extensive research was conducted to find a train ratio on the proportion of commuter trains and long-distance train traffic in Europe. A ratio that would be directly applicable to calculate the number of commuter train traffic per year based on the results of subsection 5.3.1 was preferred. However, such data could not be found.

A different approach was identified while investigating the thesis of Donners (2016). He states that in 2015, 6% of all train trips and 6% of all passenger kilometers in Europe were by international train. The preceding section, being section 5.3.1, gathered train data from Eurostat (2024) that originates from 2010-2020. In other words, generally near 2015, making this figure applicable. According to the definition of long-distance travel in this study, which is at least 200 kilometres, many domestic trips are also long-distance. This is true since many European countries are large enough to allow for rail trips that take more than 200 km. Hence, this thesis assumes that the proportion of long-distance travel, out of the total recorded train traffic, is higher than 6%, specifically 10%. To translate the acquired train traffic demands into commuter train traffic demands, the results of subsection 5.3.1 were multiplied by a factor of 0.9.

5.3.3. Estimation of 2050 Traffic

The growth formula of Equation 3.1 was applied to forecast, based on the collected traffic data, the commuter train traffic per station in 2050. The applied growth rate for the commuter trains was obtained from EY (2023), which is 1.5% growth in passenger-kilometres per year. This value corresponds to the range of Hilbers et al. (2020), which was previously discussed as a source that provides general estimations of the growth of the total number of passenger kilometres per year. Since the data here refer to commuter trains, it is assumed that this value is therefore applicable. The number of years over which this growth rate is applied depends on the time window between 2050 and the year from which the traffic data of the previous sections originate. The year in which the data was recorded is listed per commuter traffic estimate in Appendix C.

5.4. Station Capacities

This thesis defines station capacity as the summed capacity of all platform tracks to process trains, with the capacity of a track along a station platform being essentially defined by the mean occupation time per train. Zhao, Wu, and Shi (2021) assume that the platform track capacity of a typical through station is equal to 12 trains per hour. This value was verified with rail experts of Royal Haskoning DHV and it was concluded that 12 is the assumed platform track capacity for a through station. The capacity for a platform track at a terminus station was assumed to be 4 trains per hour. Whether a station is a terminus station or a through station is presented in Figure 5.5. NB: The definition of station capacity in this study is a very specific one through its focus on platform track capacity. The phrase will entail other elements of capacity in other studies, like for example the available space in a station to walk and reside.

The other requirement for calculating the station capacities, in addition to specifying the capacity per platform track, was the acquisition of the platform tracks per station. This process was executed by counting the number of platform tracks per selected station in OpenRailwayMap (Matheisen et al., 2024), which are defined as the tracks that pass directly alongside a platform. Tracks that pass through or past a station and do not provide the possibility to stop at the station are not included in the count, since they do not provide the possibility to let passengers enter or exit the train. This is in line with the way in which stations are added to the shortest rail paths in section 4.2: If a city is visited, it must also stop at the station.

If a station was encountered during the platform track quantification process that contained both terminating railways but also continuing railways, it was defined as being either a terminus station or through station based on which were in the majority.

Another remark is that not every station in the dataset that is defined as either terminus or through station visually looks like one in Figure 4.5. This can be true since Figure 4.5 is comprehensive, but not nearly complete. The station in Palermo is, for example, defined as a through station in the dataset, but visually looks like a terminus station in Figure 4.5. In comparable instances, such as Palermo, a station may appear to be a terminus station within the TEN-T network visually, but this is not actually the case when examining the underlying regional railway network.

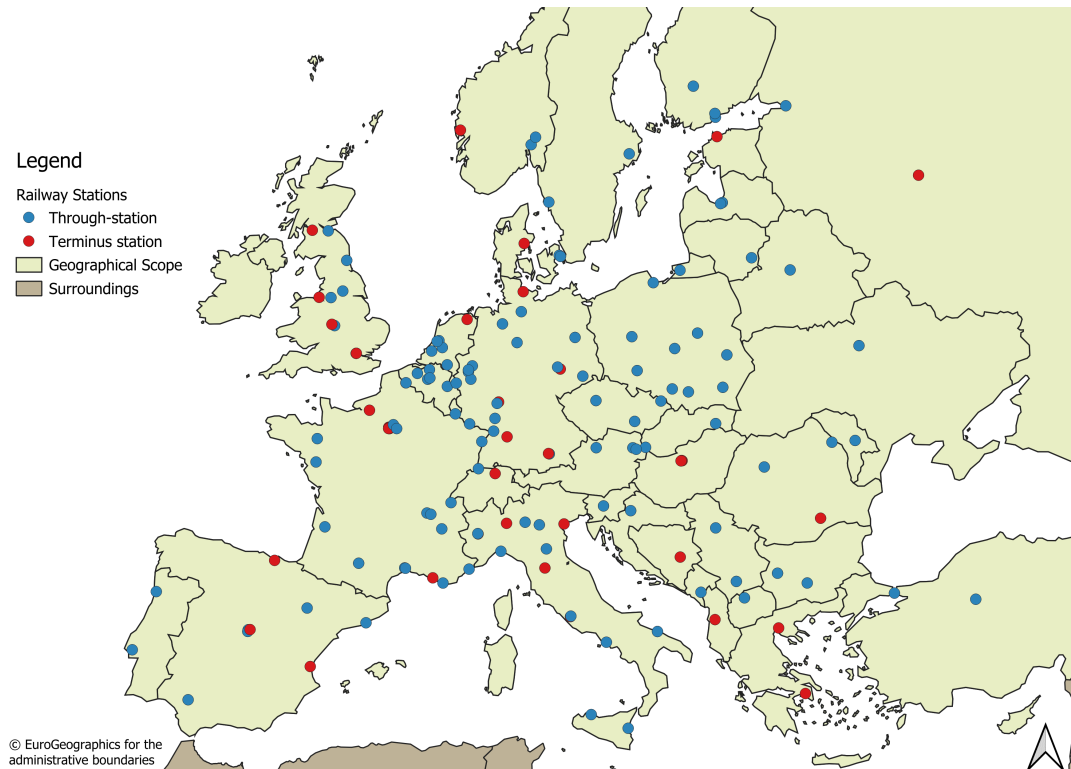


Figure 5.5: Identification of terminus stations (red) and through stations (green). Created with QGIS (2023).

After retrieval of the number of platforms and the capacity per hour, based on the typology of the station, it was possible to calculate the yearly station capacity. This was achieved by taking the hourly capacity, multiplying it by the number of platforms, and then multiplying that result by the annual operation hours. It is assumed that the percentage of night trains is negligible, and thus that the full demand of passenger trains for entry/exit is distributed between 7:00 and 23:00. This time window will henceforth be referred to as "day" and contains 16 operation hours. The results of this computation are the theoretical capacities per station, which are presented in Appendix C.

The capacities retrieved from the above analysis represent the theoretical capacities, which is defined as the maximum number of trains that can circulate on the infrastructure. The saturation analysis in this chapter also applies a commercial capacity to assess which stations are at risk of oversaturation. The commercial capacity is typically 75% of the theoretical capacity, reflecting the effective capacity of the infrastructure, considering factors such as the resilience of the system and the need to maintain regular service (Laroche, 2014). This approach highlights the tension between satisfying demand and maintaining regularity in the system (Institute for Transportation and Development Policy (ITDP), 2023).

5.5. Results of the saturation analysis

Combining the intermediate results from this chapter, which are present in Appendix C, with the formulae from chapter 3 grants the final results of sub-question Q1. These final results are the centrally-located HSR-stations that are forecast to be oversaturated or at risk of oversaturation per 2050. The results are presented in Figure 5.6, which provides input for the passenger welfare experiments in chapter 6 the conclusion in chapter 7.

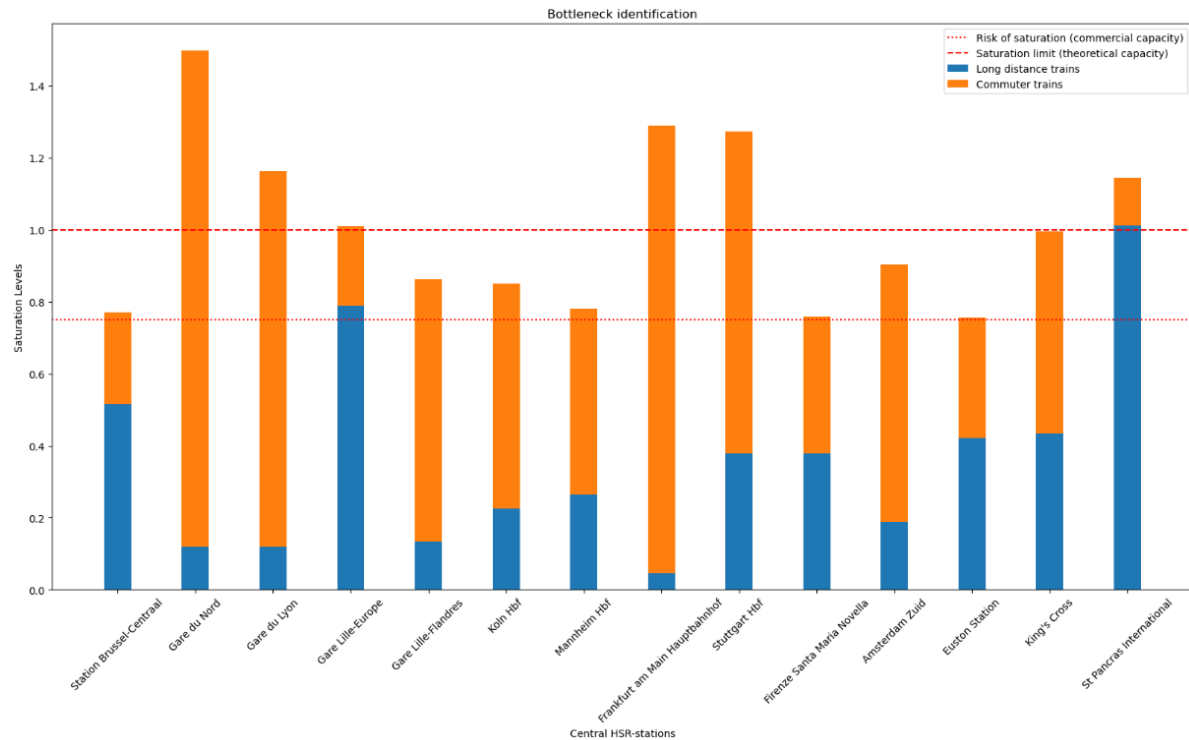


Figure 5.6: Bottleneck identification through saturation analysis. Adapted from Python (Python Software Foundation, 2024).

Figure 5.6 shows 14 potential bottleneck stations that are located across 10 cities. The results suggest that terminus stations are at a relatively high risk of over-saturation, since 9 out of 14 stations are terminus stations, see Table 5.1. This share of 64% is relatively high, since the general share of terminus stations is 36% in the evaluated set of 94 HSR-stations. It was hypothesised during the analysis of these results that the terminus stations were a more frequent choice of construction when the train was a relatively new mode, compared to the current day. A brief desk research provided the 'Opening year' results of Table 5.1 (Wikipedia, 2021). These results seem to illustrate this hypothesis, since the oldest train stations originate from the early 19th century. That the stations are old does however not mean that they have low capacities, as can be seen in Appendix C. The capacities have often been upgraded through the years during renovations.

A second observation is that many of them are located in western Europe, which is not surprising, since most of the long-distance travel demand from chapter 4 is located there in the transport model. In addition, it is hypothesised that the high train volumes in Western Europe originate from the fact that many old stations of the dataset are located there, and that the railway network, including passenger volumes, has evolved itself naturally around these stations. One can conclude that the allocation and design choice of these HSR-stations are often inefficient in the present, especially for traversing passengers.

A third observation is that the commuter passenger trains play a relatively large role in the possible over-saturation of these centrally-located stations, representing on average 62% of the demand. The

share of long-distance trains is smaller, but substantial, with on average 38%. Relocating long-distance traffic might therefore provide a number of these stations with the required traffic decrease to get under the commercial capacity limit per 2050.

A last observation concerns the relatively large role of importance that traversing passengers play in the saturation levels of these bottlenecks. The evaluated 94 HSR-stations have on average a Traversing/OD-passenger ratio of 1.9, while these bottlenecks have an average ratio of 3.9. This result has to do with the centrality of these stations in the network, meaning that many passengers will have to travel past them to reach their destination. Figure 5.7 illustrates this through the dark blue/purple lines which travel past all of the illustrated bottlenecks, the only missing station in this map is Firenze Santa Maria Novella.

Table 5.1: Characteristics of bottlenecks. Sorted by opening year.

Station	Opening year	Type
Euston Station	1837	Terminus
Mannheim Hbf	1840	Through
Gare Lille-Flandres	1842	Terminus
Gare de Lyon	1849	Terminus
King's Cross	1852	Terminus
Koln Hbf	1859	Through
Gare du Nord	1866	Terminus
St. Pancras International	1868	Terminus
Frankfurt am Main Hbf	1888	Terminus
Stuttgart Hbf	1922	Terminus
Firenze Santa Maria Novella	1932	Terminus
Brussel Centraal	1952	Through
Amsterdam Zuid	1978	Through
Gare Lille-Europe	1993	Through

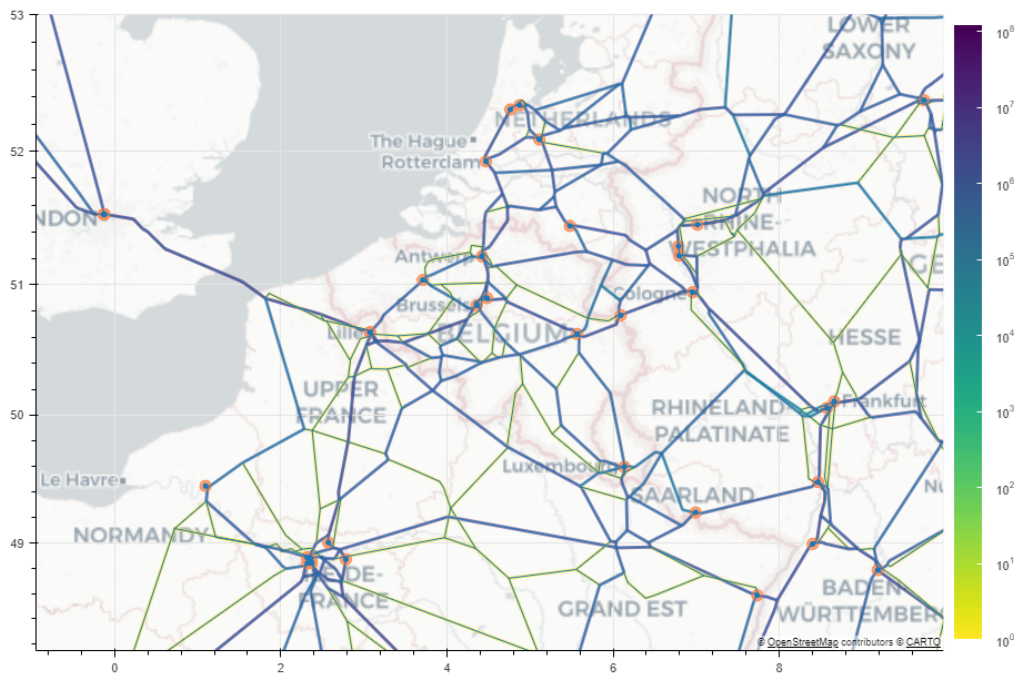


Figure 5.7: The visualised network assignment including induced demand volumes, illustrating high passenger flows at 13 of the 14 bottlenecks. The values that are aligned vertically along the logarithmic colour bar represent the yearly passenger flows per railway edge. Modelled with NetworkX (NetworkX, 2023) and visualised with Bokeh (Bokeh Development Team, 2018) in Python 3 (Python Software Foundation, 2024).

Figure 5.8 shows how the total set of 95 cities performed in the saturation analysis. It can be deduced from the figure that the vast majority of centrally-located HSR-stations are forecast to remain free of any saturation risk.

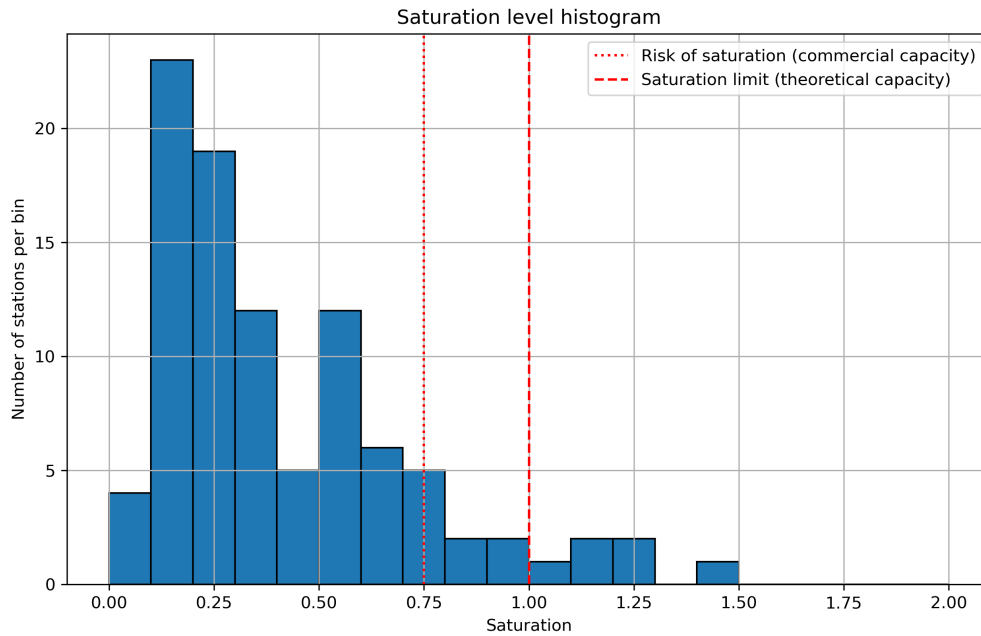


Figure 5.8: Histogram of saturation level occurrence. Adapted from Python (Python Software Foundation, 2024).

The NetworkX nodes in the Python code, which generated these results, contain all essential elements that were necessary in computing the saturation analysis. These elements are presented below to provide the reader with a comprehensive understanding of the elements that were assigned to every node in the NetworkX graph:

- **'lat'**: Latitude of the node
- **'lon'**: Longitude of the node
- **'is_station'**: Whether the node in the NetworkX graph is a station.
- **'AREA'**: The (Functional Urban) Area in which the station node is located.
- **'fid'**: The fid corresponds with the row IDs of the QGIS station node dataset and is used to match the contents of the Python NetworkX graph and the QGIS origin.
- **'ACC_TIME'**: The average access/egress time for this station node, weighted for population distribution in the area.
- **'origin/termin'**: The number of long-distance passengers that originate from the node or terminate their travel there.
- **'traverse'**: The number of long-distance passengers that traverse this station node. Both this metric and the 'origin/termin' are essential in the next step (station relocation and welfare analysis).
- **'LD_Demand'**: The total demand of long-distance trains for departure (and arrival) at a station.
- **'Com_Demand'**: The total demand of commuter trains for departure (and arrival) at a station.
- **'Cap_Station'**: The capacity of a station based on platform track capacity, the number of platforms and the type of station (terminus vs through station).
- **'Saturation_Demand'**: The saturation level of the station capacity. This is the metric that is the result of the computations up until this point and is used to answer sub-question 1.

Printed results, that correspond to the elements above, can be found in Appendix C for the identified set of 14 bottlenecks.

5.6. Limitations of the saturation analysis

This section continues the identification of research assumptions in the style of chapter 4. Therefore first describing relevant assumptions and their impacts, and then providing a table with the estimated size of the impacts and the corresponding likeliness that the assumption is an oversimplification of reality. The table that provides this overview is Table 5.2.

Then a list of assumptions:

- A26 The assumption of 350 seats per train is a conservative estimate based on Campos and de Rus (2009). Laroche (2014) illustrates this, by stating that the first generation TGV contained 377 seats, but that the average trains in France had a theoretical capacity of 450 seats per 2014, and that the 'new' Duplex double-decker trains have a capacity of 512 seats. One can conclude that 350 is a low estimate for 2050, which is impactful in the estimation of the bottlenecks. The likeliness that 350 is an oversimplification of reality is also high.
- A27 The seating capacity is assumed to be the passenger capacity in the context of long-distance trips. Essentially, this means that passengers on long-distance trips needs a seat. People can not choose to book a ticket which allows them to stand. The impact of this assumption on the capacity per train, and therefore the saturation analysis, is high, but it is expected that this assumption is close to the truth.
- A28 This study assumes, for the use of Equation 3.15, that traversing passenger and OD-passenger equally impact the train traffic at a station. There are however arguments to be made that this approach is too simplistic.
 - Overestimation argument: The approach sums all originating passengers, terminating passengers and traversing passengers up to one variable LD_Pass of number of passengers per station. Inherent to this approach is that every individual is modelled to occupy one seat in one specific train during the train's dwell time at a platform, therefore equally impacting the train demand. This is true for traversing passengers that continue their journey and stay in the same seat during the halt, but terminating and originating passengers might very well interchange one specific seat during the train's dwell time. In the case of such a seat reassignment from one destination passenger to another origin passenger, they effectively use the train's occupation time of a platform track only once instead of twice.
 - Underestimation argument: A traversing passenger might need to transfer from a train that terminates its journey at one platform and switch to a train that departs from another platform. In such a case, the passenger contributes to two platforms being occupied instead of one. This statement is true for traversing passengers that need a transfer where either the arriving train terminates its line service, or the departing train initiates its line service, or both. This situation also prevents destination and origin passengers to switch the same seat (the situation of the overestimation argument).

The applicance of the Equation 3.15 can be interpreted an overestimation as well as underestimation of the long-distance train demand. They therefore cancel each other out to some extent. Albeit that the overestimation argument is expected to be more impactful. The impact of this assumption is concluded to be medium impactful, while the likeliness that this assumption oversimplifies reality is high.

- A29 It is inherently assumed in this thesis that commuter train traffic will remain to be allocated at the central stations, and that it is not permitted to be negatively impacted by the increasing number of long-distance trains. This is why this research suggests to relocate HSR-services. This is an impactful decision, since this means that high-speed rail can not increase its capacity in existing railway stations by overtaking platforms from conventional rail. The reasoning for this is that the introduction of HSR has led to welfare loss of conventional rail passengers in China Li et al. (2020). The HSR introduction reduced the frequency of conventional train service, leading to many conventional train passengers to be undeserved in their day-to-day work or school life. Low-income populations were affected most in these situations, because they are more dependent on

cheaper conventional trains (Cheng and Chen, 2021). The expansion of HSR has also been at the expense of conventional train travel in Europe, namely in Spain and Italy, where a decline of 24% and 32% was observed (Banister and Givoni, 2013) between 1995 and 2011. This does not necessarily imply a welfare loss, since it is plausible that HSR is simply a better alternative and thus substitutes the conventional rail services, but it can also not be ruled out that there is no welfare loss. In conclusion; it is assumed for the saturation analysis that commuter trains remain allocated at centrally-located station and that HSR will not overtake capacity from the conventional rail services, to guarantee that the implementation of the TEN-T railways does not lead to socio-economic decline. The consequence of this assumption is that stations have a higher chance at saturation. The likelihood that this assumption is an oversimplification of reality is deemed low, since it is expected that local governments will try to uphold the role of centrally-located stations for commute.

- A30 This study assumes a distinct separation between long-distance trains and commuter trains, which is effectively the confinement of <200 km for commuter trains and >200 km for long-distance trains. It might however also be possible that people commute a bit more than 200 kilometre, say for example because they work in Brussels but effectively live in Paris (>200km travelled distance). HSR allows for such trips since the train ride between them takes only 1 hour and 38 minutes (Google Inc., 2024), and it is expected that other HSR-lines might provide for such long commuter trips in the future as well. For instance, this thesis assumes an average HSR speed of 215 km/h, meaning that one could do a commute travel of 200 km in less than 1 hour in-vehicle time. The impact of this is defined as low since not many employees are expected to frequently travel such distances. The likeliness that this study oversimplifies through this statement is however expected to be substantial, especially since these long-distance commutes are, almost certainly, not present in the passenger distribution matrix that is grounded in air passenger data (Grolle et al., 2024).
- A31 It has been assumed, based on an extrapolation of data from Donners (2016), that 10% of all train traffic passenger-kilometres in Europe originate from long-distance travel, being >200 kilometres. This value, might, in hindsight be on the low end. Banister and Givoni (2013) in 1995, HSR represented a mere 9.4% of train passenger-kilometres in Europe, a figure that rose dramatically to 27.1% by 2011. This value of 27.1% HSR seems much higher than the value assumed in this study, but this can largely be explained by the fact that Banister and Givoni (2013) takes 11 EU countries into account, which all contain HSR to some extent. Specifically containing France and Spain, where HSR surged to 58% and 49% respectively of total train passenger-kilometres in 2011. This thesis, on the other hand, takes 42 countries into account of which a substantial number do still not contain HSR in 2050. It is therefore expected that the 10% is a relatively low estimate for long-distance traffic, expressed in passenger-kilometres, but it is not that far from the truth as Banister and Givoni (2013) initially suggests. Impact is expected to be medium since it would change the commuter train input in the saturation analysis to a slightly lower value.
- A32 This chapter assumes a growth factor for commuter trains of 1.5% on the basis of EY (2023). The value fits the range of growth factors of Hilbers et al. (2020), which implies that 1.5% assumes relatively strong economic growth. This approach, of assuming a relatively high growth percentage, is useful in identifying potential bottlenecks, which is the goal of this chapter. It is however a discrepancy in comparison to the relatively low transport growth that was assumed for long-distance travel in chapter 4, being only 13% between 2024 and 2050. The approach of selecting a conservative percentage there, to not eventually overestimate passenger welfare effects, also makes sense, but it does not align with the assumed 1.5% here. This is an inconsistency, which provides a distorted ratio of the contribution of commuter and long-distance trains in Figure 5.6. The impact of assuming 1.5% is therefore high, although the likeliness is medium since it is a realistic growth scenario (Hilbers et al., 2020; EY, 2023).
- A33 This research assumes stations to be either a terminus type station or a through-type station, based on which types of platform tracks form the majority in OpenRailwayMap (Matheisen et al., 2024). The capacity per platform track is derived from this typology, being either 4 trains per hour or 12 trains per hour, which makes the typology definition crucial in the saturation analysis. This assumption might however be too straightforward. The typology can in reality also be a mix of terminus and through-station. Examples of these include Edinburgh Waverley and Bologna Centrale, with Edinburgh Waverley containing 14 terminus type tracks out of 20 platform tracks and

Bologna Centrale containing 11 terminus type tracks out of 20 platform tracks. Both have therefore an underestimated capacity by assuming that they are purely terminus stations. Although the impact of this assumption is high for the few stations which it concerns, not many stations were found that have such a mix of terminus and through-type platform tracks, making the overall impact low of the assumption low. The likelihood of oversimplification is high, since there are sufficient examples that illustrate that such a binary approach is too simple.

- A34 This chapter assumes that there can only be one train at a time that dwells on the platform track alongside a platform. While in reality, long platforms sometimes also host two trains at a time. This assumption therefore underestimates the capacity of railway stations. Although it has to be taken into account that trains are increasing in length (European Commission, 2021b), which makes it less likely that numerous platforms will simultaneously host two long-distance trains at the same time in 2050. The impact of this underestimation is therefore estimated to be moderate, while the likelihood oversimplification is high.
- A35 Traffic demand is assumed to be uniform throughout the day, excluding the effects of rush hours and their corresponding demands. The impact of this assumption on the bottleneck identification results is high, since stations will reach saturation limits much sooner for these rush hours than they will for the entire assumed day period (7:00-23:00). Effectively, this assumption excludes the possibility that certain time-slots will make the station saturated much earlier than 2050, which could start the discussion on capacity expansion or services relocation sooner than expected on the grounds of this study. The impact of this assumption is high, as is the likelihood that the definition of capacity of this research oversimplifies reality.
- A36 Although the use of night-trains for long-distance travel is increasing (Heufke Kantelaar et al., 2022), this thesis assumes that the amount of night trains (23:00 - 7:00) relative to the amount of day trains (7:00 - 23:00) is negligible. Both Heufke Kantelaar et al. (2022) and Weißhaar (2024) find that the willingness to take the night train is substantial. Weißhaar (2024) even finds a potential of 40% market share in the base scenario of a stated preference survey, where respondents are offered to choose between a day HSR-train, night HSR-train and flight. The study however also recognises that the current supply of night train services is still low. This thesis assumes that this supply-side stays remains low up until 2050, and is therefore negligible.

Table 5.2: Overview of assumptions of the saturation analysis.

ID	Assumption	Impact of assumption	Likelihood of oversimplification
A26	The assumption of 350 seats per train is a conservative estimate based on historical data.	High	High
A27	The seating capacity is assumed to be the passenger capacity in the context of long-distance trips.	High	Low
A28	Traversing passengers and OD-passengers equally impact train traffic at a station.	Medium	High
A29	Commuter train traffic will remain allocated at centrally-located stations.	High	Low
A30	There is a distinct separation between long-distance trains (>200 km) and commuter trains (<200 km).	Low	Medium
A31	10% of all train traffic passenger-kilometres in Europe originate from long-distance travel (>200 km).	Medium	High
A32	A growth factor for commuter trains of 1.5% is assumed based on economic growth projections.	High	Medium
A33	Stations are either terminus type or through-type based on platform track majority, impacting capacity estimates.	Low	High
A34	Only one train can dwell at a platform track at a time.	Medium	High
A35	Traffic demand is assumed to be uniform throughout the day, excluding rush hour effects.	High	High
A36	The amount of night trains (23:00 - 7:00) relative to day trains (7:00 - 23:00) is negligible.	Medium	High

Passenger Welfare Effects of HSR-Station Relocation

This chapter generates passenger welfare effects for a range of experiments, analyses them and eventually puts them in the context of social cost benefit analyses. In doing so, it provides the input to answer the five remaining research questions.

6.1. Iteration set-up of the Transport Model

Every experiment in this chapter was run as an iteration of the Transport Model. Applying for each experiment different station layouts in the city area and, for Q3 and Q4, also different networks. This section describes how the passenger welfare effects were estimated for two groups of passengers in the 2050 network and then how the passenger welfare effects were discounted to a value for 2024. The first group is the initial distribution of passengers, which was established in subsection 4.4.1, the second group contains the induced demand passengers. The cause of this differentiation between two groups is described after presenting the procedure for the first group.

The procedure in Python to estimate passenger welfare effects for the initial passenger volumes, in accordance to section 3.4, was the following:

1. The experiment procedure is initiated by changing the geographical inputs of the model. This concerns the loading of a new set of edges and stations for Q3 and Q4, or simply switching the presence of certain stations in Q2. In general, three types of input are required for three types of experiments. One in which both central and peripheral HSR-stations exist, one in which peripheral only station(s) exist, and one in which only central station(s) exist. These two alternatives has been visualised in Figure 1.1 in chapter 1. In Q3, this also concerns changing the access and egress distance matrices of airports that see their accessibility improved as a result of the relocation of the HSR-service to that airport.
2. The logsum is calculated and stored per OD-pair. This is a step that has to be done for every desired experiment. The logsum is the expected utility of a choice set, which a hypothetical passenger experiences when making a decision about their way of travelling between an OD-pair. It is computed by summing the exponentiated utility matrices for both the rail, air, and road modes, as mathematically presented in Equation 3.16.
3. The stored logsums of the experiments are compared per city and per type of experiment. Subtracting the logsum of the scenario with new infrastructure ($t=1$) by the one without ($t=0$) grants the so-called consumer surplus in utils per OD-pair. This difference reflects the change in the expected utility for a representative individual due to the policy change.
4. To convert this surplus in utils per OD-pair into monetary terms, the difference is divided by the marginal utility of income, denoted as γ . The γ is assumed to be the negative of the travel cost taste parameter (β_{TC}). This aligns with economic theory, which states that utility and cost parameters are typically inversely related. This value is retrieved from Table 4.13.

5. Finally, the total welfare impact on all initial passengers is assessed by multiplying the calculated per-capita consumer surplus per OD-pair by the number of potential consumers per OD-pair, as they were established in the 2050 passenger distribution matrix. This multiplication step distributes the per capita surplus across the entire affected population, thereby providing a measure of the total welfare change per 2050. The passenger distribution matrix that is used for this procedure is that of the base-model, since that is the reference situation.

To generate the correct passenger welfare values for the entire network, the benefits that induced demand passengers experience should also be included. However, the approach to estimating these is slightly different from the approach described above.

It is assumed that the induced passengers start travelling by rail at least a couple of years prior to the station infrastructure change that is modelled for the year 2050. Many are probably generated much earlier, but this is a conservative assumption. This means that they would experience the benefits or losses of the change in infrastructure as any other rail passenger would that travels across that infrastructure. Since these induced passengers are generated as a result of new rail infrastructure, in accordance to the new edges as presented in Figure 4.16, it is assumed that they are fully committed to the rail mode. They cannot switch to other modes and therefore will not receive benefits of the airport accessibility improvement in Q3.

Since they can only opt for rail, and therefore receive full benefits of the rail service changes, the logsum-based formula can be simplified from Equation 6.1 to Equation 6.2 for induced demand passengers:

$$\Delta CS = \frac{1}{\gamma} \left[\ln \left(\sum_{j=1}^J \exp(V_j^{t=1}) \right) - \ln \left(\sum_{j=1}^J \exp(V_j^{t=0}) \right) \right] \quad (6.1)$$

where: ΔCS = Consumer surplus i.e. passenger welfare effect in [€]
 γ = Marginal utility of income i.e. $-\beta_{TC}$ in [utils/€]

$$\Delta CS = \frac{1}{\gamma} [V_{rail}^{t=1} - V_{rail}^{t=0}] \quad (6.2)$$

where: ΔCS = Consumer surplus i.e. passenger welfare effect in [€]
 γ = Marginal utility of income i.e. $-\beta_{TC}$ in [utils/€]

The adapted procedure for estimating passenger welfare effects for the induced demand passengers per 2050 is provided below and includes references to the adapted logsum formula of Equation 6.2. The description below skips step 1 of the previously described approach, since it has already been done if you perform those steps first. Step 4 is identical for both procedures and has therefore been excluded from the enumerated list below to prevent textual repetition. The adapted procedure has been applied as follows:

2. The weighted rail utility per OD-pair is calculated and stored in a matrix for every experiment. This matrix is the so-called rail utility matrix. The matrix contains the expected utility for every rail choice set per OD-pair.
3. The stored rail utility matrices of the experiments are compared per city and by type of experiment. This is done according to Equation 6.2, granting the consumer surplus in utils per OD-pair for the induced demand passengers.
5. Finally, the passenger welfare effect, as experienced by the induced passengers, is assessed through multiplication of the calculated per-capita consumer surplus per OD-pair with the number of induced passengers per OD-pair. The set of induced passengers per OD-pair that is used for this procedure is that of the base-model, since that is the reference situation.

After the execution of both procedures, the effects are summed to a total passenger welfare effect and then discounted to a monetary value that is correct for 2024 according to Equation 3.18. The discount rate that was applied in this process is assumed at 4%. The discount rate can be interpreted as the societal return expectation for a public investment or project. It represents the percentage by which anticipated future benefits are adjusted to the project's base year. The following paragraphs detail why

the 4% was selected.

The Ministry of Finance of The Netherlands (2020) defines a discount rate of 2.9% for CBAs where the benefits have a non-linear relationship to the state of the economy. Their report explicitly defines "journey time benefits (for persons and cargo) that are gained when a capacity bottleneck is eliminated" as an example of such a nonlinear relationship. The value of 2.9% would therefore have been very applicable as the discount rate r for Equation 3.18. At least if this study had been conducted in a purely Dutch context. However, given the broader geographical scope of this study, European sources were consulted.

For the 2014-2020 programming period, the European Commission recommends using a social discount rate of 5% for major projects in Cohesion countries and 3% for other Member States, as outlined in Annex III of the Implementing Regulation on application forms and CBA methodology (European Commission, 2014). Cohesion countries are those with a gross national income per capita below 90% of the EU average. Member States can establish a different discount rate benchmark if they provide justification based on economic growth forecasts and other relevant parameters, ensuring consistent application across similar projects within the same country, region or sector.

Almost all relocation experiments in this study occur in countries that are not Cohesion countries (European Commission, 2014), so a discount rate of 3% or 4% would initially seem appropriate. The decision was made to use the latter. This choice enables a comparison with SCBA calculations of peripheral HSR stations in the paper by Widmer and Hidber (2000). The analyses in that study employ a discount factor of 4%, allowing for a consistent comparison of these figures with the results of this thesis. This rate is inflation-adjusted.

6.2. Potential of existing peripheral stations

This section aims to provide context on the efficiency of existing peripheral stations that provide an HSR-detour in generating passenger welfare, in comparison to only having centrally-located stations. It is therefore explicitly not based on the defined bottlenecks of chapter 5, but on a set of existing peripheral stations that provide HSR-detours.

This section provides input for the answer to sub-question 2. This sub-question is useful for this research since it provides monetary passenger welfare results that put the results of Q3 and Q4 in a context of realistic, i.e. existing, situations. In addition to this, the results of this section provide input for answering Q5 ('which conditions benefit') and Q6 ('relative size of welfare effects in SCBA').

A benefit of this section is that results are easily generated, as the base-scenario network (Comprehensive TEN-T 2050) already contains these peripheral stations. Therefore, the results were quickly generated by including / excluding stations from the base-model and comparing the iterations according to section 6.1, without the need to create or adapt the rail infrastructure in QGIS (2023). To summarise, this section seeks to present authentic passenger welfare effects and to contribute in the answering of subsequent sub-questions.

The selection of experiments for this research is constrained by the definition of the station definition of Q2, being: 'existing HSR-stations, which provide a detour in the city outskirts by 2050'. Translating this definition to constraints generates the following set:

- The station must provide a detour that excludes central stations, i.e. a next or previous halt can not be a central station;
- The station must be a through station, not a terminus station;
- The location must be located in a peripheral area, but not necessarily outside of the GHS urban centre (OECD, 2023).
- The station must provide HSR-services.

The selected cities are presented in the results table of Table 6.1. Per city, three iterations are executed for Q2:

- ‘Central only’ scenario: Only centrally-located stations are present in the transport model. This scenario is used as $t=0$ in Equation 3.16.
- ‘Peripheral only’ scenario: peripheral only stations are present in the transport model. It is used as $t=1$ in Equation 3.16 and abbreviated to PO.
- ‘Both’ scenario: Both peripheral and central stations are present in the model. Is used as $t=1$ in Equation 3.16.

The ‘peripheral only’ may sound as the most fitting scenario for this thesis since it fully relocates the HSR-services, but appliance of this scenario generally also leads to many OD-passengers that have to make an inefficient detour and see their access/egress time increase. That is why the ‘Both’ scenario was introduced, which allows for relocating HSR-services, but not relocates them completely.

The disadvantage of the ‘Both’ scenario is the following: Since most passengers in the model take the path that maximises their utility, traversing passengers will in general take the peripheral detour station (if strategically located), while the OD-passengers take the central station (if strategically located). This would mean that there are unlimited services that supply every passenger with their preferred rail route, being either an urban or peripheral route. This is too optimistic for reality.

The benefit of co-existent services theoretically lies between the ‘Peripheral only’ result and a value that is a bit more positive than the ‘Both’ result, assuming that the approach of this study is accurate. Values in this range provide the order of magnitude of passenger welfare benefits when the railway operator would direct some HSR services to the city centre and others to a peripheral station, while not completely satisfying every passenger’s preferred route. The reason for stating that the actual benefit could in theory even be ‘a bit more positive’ than the ‘Both’ result is that a small share of passengers in this model make suboptimal decisions, which has to do with the fact that the transport model applies a probabilistic assignment and not an All-Or-Nothing assignment. If all passengers would make their optimal decision, the passenger welfare benefits could be even higher, assuming unlimited services. In practice, however, the actual benefits would presumably lie between ‘Peripheral only’ and ‘Both’, if the results of this study are assumed accurate.

Applying the discussed procedures in combination with the formulae of section 3.4 generates the results as presented in Table 6.1. As described in chapter 3, the total consumer surplus results are referred to as $\sum CS$. This is done in Table 6.1 and subsequent tables for editorial reasons.

Table 6.1: Passenger welfare effect results of experiment set Q2.

ID	City	$\sum CS$ 2050; PO [million €/year]	$\sum CS$ 2050; Both [million €/year]	$\sum CS$ 2024; PO [million €/year]	$\sum CS$ 2024; Both [million €/year]
Q2.1	Birmingham	226	235	81	85
Q2.2	Brussels	-323	-32	-117	-12
Q2.3	Copenhagen	106	74	38	27
Q2.4	Frankfurt	517	443	187	160
Q2.5	Leipzig	-35	-4	-13	-2
Q2.6	Lyon	255	326	92	118
Q2.7	Montpellier	103	93	37	34
Q2.8	Paris	925	820	334	296
Q2.9	Vienna	-317	-55	-114	-20

A couple of results stand out in having very positive results, including Birmingham and Lyon. That is why the passenger distribution maps from Python, visualised with the Bokeh package, are included here for these two cities. Figure 6.1 and Figure 6.2 clearly show that more passengers take the peripheral station in the base- transport model than that there are passengers that travel towards the city centre. For inspection of zoomed network lay-outs from QGIS, the reader is referred to Appendix D. In this appendix, the reader can find respectively Figure D.1 for Birmingham and Figure D.6 for Lyon.

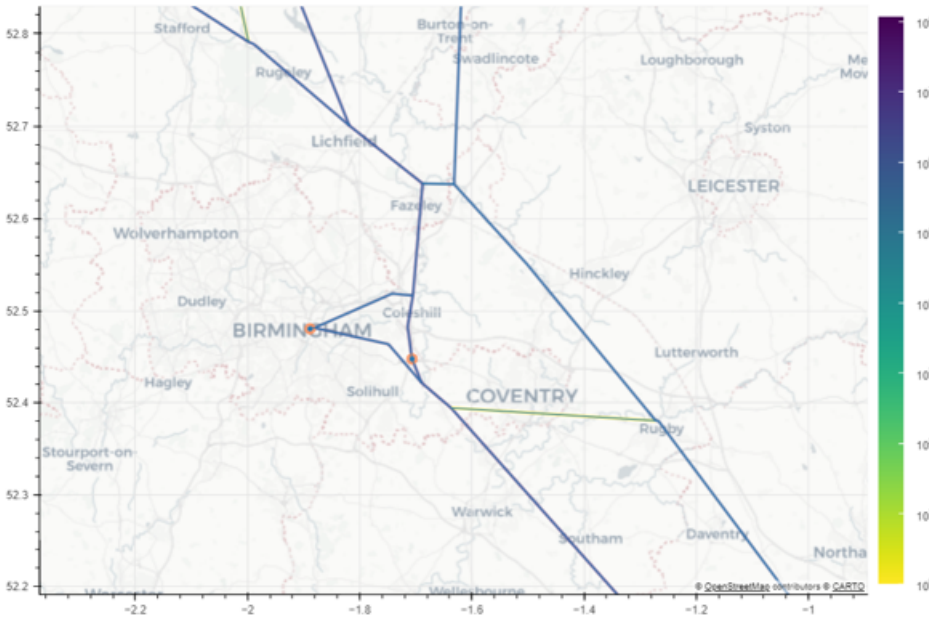


Figure 6.1: Passenger distribution around Birmingham in base model ('Both' scenario).

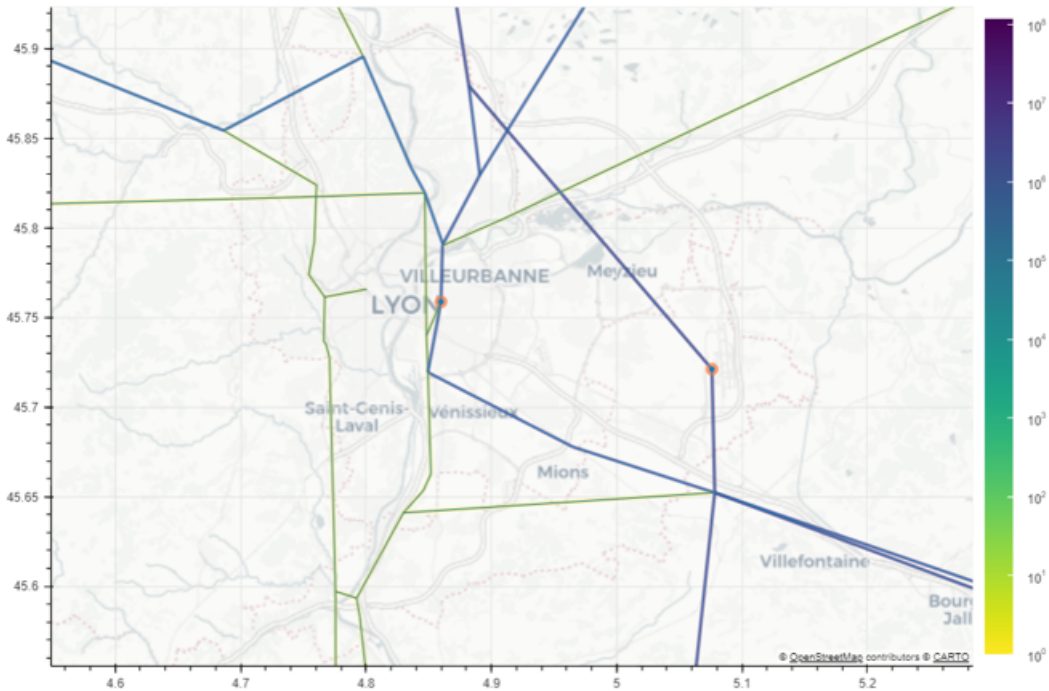


Figure 6.2: Passenger distribution around Lyon in base model ('Both' scenario).

The results presented in Table 6.1 can be classified in three categories.

Firstly, there are positive results, where 'Both' is the most favourable. This indicates that peripheral stations are preferred by traversing passengers while central stations are favoured by origin-destination (OD) passengers, as seen in cities like Birmingham and Lyon.

Secondly, there are positive results where 'peripheral only' is most favourable. This suggests that the peripheral station is not only a better option for traversing passengers, aligning with the expectations set out in the hypothesis, but is also preferred by OD passengers. This preference can be attributed to a relatively short access/egress distance, which was estimated through the weighted population density approach, combined with a higher average access/egress speed to peripheral stations compared to central stations. Examples of this phenomenon can be observed in Copenhagen, Frankfurt am Main, Montpellier, and Paris. The frequency of this result type, where OD-passengers prefer the peripheral station to the central station, implies that the access/egress speed approach overestimates the accessibility of peripheral stations. One would assume that the OD-passengers are in general not fond of a station which is further away of the city. This impact of this assumption, being A13 on the access/egress speed approach, has previously been described as high in subsection 4.6.3 and is also discussed in section 7.2.

Lastly, there are negative results, where incorporating the peripheral station into the high-speed rail (HSR) services decreases passenger welfare, and replacing the central station leads to even worse outcomes. In reality, this would be a situation in which the location of the peripheral station only benefits those who need to be in that specific area, but decreases the welfare of all other passengers. The transport model can yield these negative results because passengers travel to all potential stations in an urban area, with a significant preference for the optimal station. However, since the network assignment applied is not All-Or-Nothing, where passengers would only visit the optimal station, but rather a probabilistic assignment in accordance with the Path Size Logit, these negative results can emerge when adding a suboptimal station to the network. Cities such as Brussels, Leipzig, and Vienna exemplify this scenario.

Further findings of these results are discussed in chapter 7.

6.3. HSR-service relocation to the airport

This section presents the approach of the Q3 experiments and the corresponding results. These experiments relocate HSR-services from the bottleneck stations to a hypothetical HSR-station at the airport, provided that the airport is located in a peripheral part of the functional urban area (FUA). Effectively, the airports that were selected as hypothetical HSR-stations were selected on the following grounds:

- The airport must be located in the FUA of the city, which has been assumed to be the commuting zone of the city (OECD, 2023).
- The airport must be located outside of the GHS urban centre of the city (OECD, 2023). This provides the possibility of HSR-services to remain speed, which is expected to be necessary to generate positive welfare effects.
- The airport must be located in a squared kilometre cell of Eurostat (2020a) that is defined as peripheral, and at least two of the four directly adjacent cells must also be defined as peripheral to ensure feasible adaptation of the rail network. The definition of peripheral is provided in the list of key definitions of section 1.7.

From the bottleneck list of Figure 5.6, the cities of Mannheim and Florence were excluded, respectively, because there is no airport in the FUA or that the airport located in the GHS urban centre (OECD, 2023). The other 9 cities that contain at least one bottleneck station are provided in Table 6.2, including the corresponding airports to which the HSR-services are relocated. Three of them have essentially already been done in Q2, since they are already connected to the network. This section therefore focusses from here on only on the six new cases.

The cities of Amsterdam, Brussels Budapest, Cologne, Lille and Stuttgart, all contain one feasible airport, which is located in the FUA but outside of the GHS urban centre (OECD, 2023). In all cases except for Amsterdam, they were not yet connected per rail so the network had to be adapted in QGIS. In the case of Amsterdam, the airport Schiphol is already connected per high-speed rail, which means that relocation of HSR-services did not require an infrastructure change. The potential passenger welfare benefits were, prior to the experiment, expected to be negative or slightly positive when relocating

Table 6.2: Experiment set for Q3.

City	Iteration	Airport Name
Amsterdam	Performed in Q3	Amsterdam Airport Schiphol
Brussels	Done in Q2	Brussels Airport
Budapest	Performed in Q3	Budapest Liszt Ferenc International Airport
Cologne	Performed in Q3	Cologne Bonn Airport
Frankfurt Am Main	Done in Q2	Frankfurt Am Main Flughafen
Lille	Performed in Q3	Lille-Lesquin Airport
London	Performed in Q3	London Gatwick Airport
Paris	Done in Q2	Charles de Gaulle International Airport
Stuttgart	Performed in Q3	Stuttgart Airport

to Schiphol since it does not provide a peripheral detour.

The two remaining cities, London and Paris contained two airports within the FUA. The only feasible one due to the constraints was Charles de Gaulle airport for Paris. However, in the context of London, both Gatwick and Stansted were feasible. Of these two, Gatwick has larger air passenger volumes (Eurostat, 2023) and a higher potential of servicing traversing rail passengers, according to the network assignment of the base-model. For this reason, Gatwick was selected as the airport for London.

The HSR-stations were created in the point layer in QGIS that contains all station nodes. The locations were defined at some distance in front of the airport entrance, based on where OpenStreetMap shows where there are no buildings (OpenStreetMap, 2024). The exception is when a railway station already exists, in that case the HSR-station is assumed to also be located there. This exception only applies to Cologne.

Besides the potential of improved rail utility, the results of this sub-question may also contain improvements in air utility. This potential arises under the assumption that peripheral High-Speed Rail (HSR) stations, if constructed, are realised in conjunction with a robust public transport (PT) connection to the city. This could lead to an improvement of the local accessibility of the airport.

Of the six cases discussed, five airports are not yet equipped with HSR-stations and may therefore experience improved access/egress time due to new PT connections. This possibility is determined in a similar way to the determination of access/egress times for the peripheral HSR-stations at airports in section 4.2. The approach entails the comparison of the access/egress airport approach (AA) and the access/egress railway station approach (RA), where RA represents a situation in which the station is well attached to the PT network. To recap, the two access/egress approaches were defined in the following way:

- The access/egress approach for airports (AA) from section 4.2 was adapted from Grolle et al. (2024) and changed to include a 35% PT mode share. This model assigns choice probabilities to flight legs for each origin-destination pair, and requires in this probability estimate the access/egress times between city and airport. The access/egress distances are based on geodistances between the city centre and airport, and are therefore less correct than in the RA. The travelled distances for the 65% car are, however, assumed to be more accurate since they were generated using OpenRouteService (Heidelberg Institute for Geoinformation Technology, 2022). The comparison in Table 6.3 concerns purely the city-to-airport access/egress time.
- The access/egress approach for peripheral railway stations (RA) was described in section 4.2, where distance calculations were based on the QGIS weighted population method. The modal split and speeds were estimated on three reference peripheral stations, being Charles de Gaulle, Marne-la-Vallée-Chessy, and Lyon Saint Exupéry. These peripheral stations are well-connected per PT transit and thus serve as a baseline. This approach in QGIS was applied to generate access/egress times for the five new hypothetical peripheral HSR-stations.

The comparison between these two approaches is presented in Table 6.3. If the airport access and egress times (AA) are improved by the new HSR-station access and egress time (RA), its improved access/egress time is provided in bold text. If it remains the same it is presented in plain text. The underlying logic here is that the access/egress times of airports can only improve when a new HSR-station is constructed, it will not become worse.

Table 6.3: Access/egress time comparisons according to airport approach (AA) and rail approach (RA), with resulting access/egress time for the airports of Q3.

City	Airport	Acc/egr AA [h]	Acc/egr RA [h]	Result airport acc/egr [h]
Cologne	Cologne Bonn Airport	0.69 / 0.71	0.74	0.69 / 0.71
Budapest	Budapest Airport	0.82 / 0.84	0.70	0.70
London	London Gatwick Airport	1.45 / 1.47	1.56	1.45 / 1.47
Stuttgart	Stuttgart Airport	0.69 / 0.72	0.66	0.66
Lille	Lille-Lesquin Airport	0.57 / 0.59	0.44	0.44

In 3 out of 5 cases of Table 6.3, the access/egress time from the city area to corresponding airport/HSR station improved. These three new values were applied in the city-to-airport-time matrix and corresponding adapted code from Grolle et al. (2024), as has been described in the air travel attribute part of section 4.2. This produced new airport access and egress time matrices for Budapest, Stuttgart, and Lille, which are lower than their original counterparts, thus leading to positive consumer surplus.

A brief reality check was performed through Google Inc. (2024). The RA assumes that a peripheral rail station is well connected through PT, just like the three French stations on which it was based, which would mean that airports that are not connected through PT-transit will improve their accessibility if an HSR-station is built. This expectation applies to the cases of Budapest Ferenc International Airport and Lille-Lesquin Airport, where currently only shuttle buses exist. Thus, these airports would benefit from a transit mode that is not dependent on road traffic. This matches the results in Table 6.3. However, this cannot be said for Stuttgart, which in reality is already connected by the S-Bahn city rail (Google Inc., 2024). Therefore, two out of three airport access/egress improvements in this comparative approach match reality. No changes were applied based on this check, but its considerations are included in the limitations section of this chapter.

The next step in the preparation of the experiment was the adaptation of the railway network, i.e. inclusion of a new peripheral HSR-detour. This step was performed in QGIS, which was set to automatically update the distances of the edges. The following guidelines were applied for the creation of the peripheral detour in both Q3 and Q4. The first one concerns a constraint (C1), the second one an objective (O1), the subsequent bullets concern procedural steps (P1, P2, P3 and P4) and the last two concern exemptions (E1 and E2).

- C1 The start, station, railway junctions, and end of the peripheral detour must be located within the urban area (FUA).
- O1 The aim is to minimise HSR-construction in densely populated areas, which would lead to relatively low construction costs. The population grid of Eurostat (2020a) was applied in the realising this objective. Every km² cell that is crossed and is peripheral, has a relative cost of 1, every urban cell that is crossed has a cost of 3 and every central cell that is crossed has a cost of 5. The aim is to construct a path with the minimum level of cost. The airside area of the airport is prohibited to be used in drawing the HSR-detour. The use of existing parts of HSR infrastructure is free of costs and allows the route to move through populated areas.
- P1 The drawing procedure is initiated by drawing the shortest possible edge from one of the incoming HSR-infrastructure to the station option. A route is then constructed, in accordance with the rules above, to the nearest other HS-railway as seen from the original edge. This nearest other HS-railway can also be an element of an already existing peripheral detour like in the case of Paris. If there is a third HS-railway which is less than 45° degrees away (as seen from the city centre) from the second HSR line, this one is also included in the peripheral detour if it is headed in another direction than the second.

- P2 The previously existing network from the base-model is unchanged, except for cutting edges at the beginning and end of the detour to ensure that the network is navigable.
- P3 The design of the peripheral detour is crafted without incorporating geometric constraints such as maximum allowable curve per unit of distance. Instead, the detour is manually delineated within QGIS to visually approximate realistic curvature, aiming for feasibility while limiting the manual workload.
- E1 A T-structure is created if the experimental station is located directly in the pathway of an incoming high-speed railway. This rule is applied for the Q4 experiments of Cologne W, Frankfurt SW and Brussels NE.
- E2 If a conventional railway intersects the manually constructed HSR-detour, a junction is only made under two conditions. One, the conventional railway line is headed in a direction which can not be reached per high-speed rail; and two, the conventional railway has a non-zero link flow. This approach was applied because it is unlikely from a service- and cost perspective that junctions will be made between all HSR and conventional railway lines, but it is likely that these are made between essential railway trajectories for long-distance travel.

An example route, with the underlying population density grid, is presented in Figure 6.3. It clearly visualises that the aim was to minimise construction through the populated areas, but also illustrates that it is infeasible to fully prevent that. The results of the Q3 experiments are presented in Table 6.4.

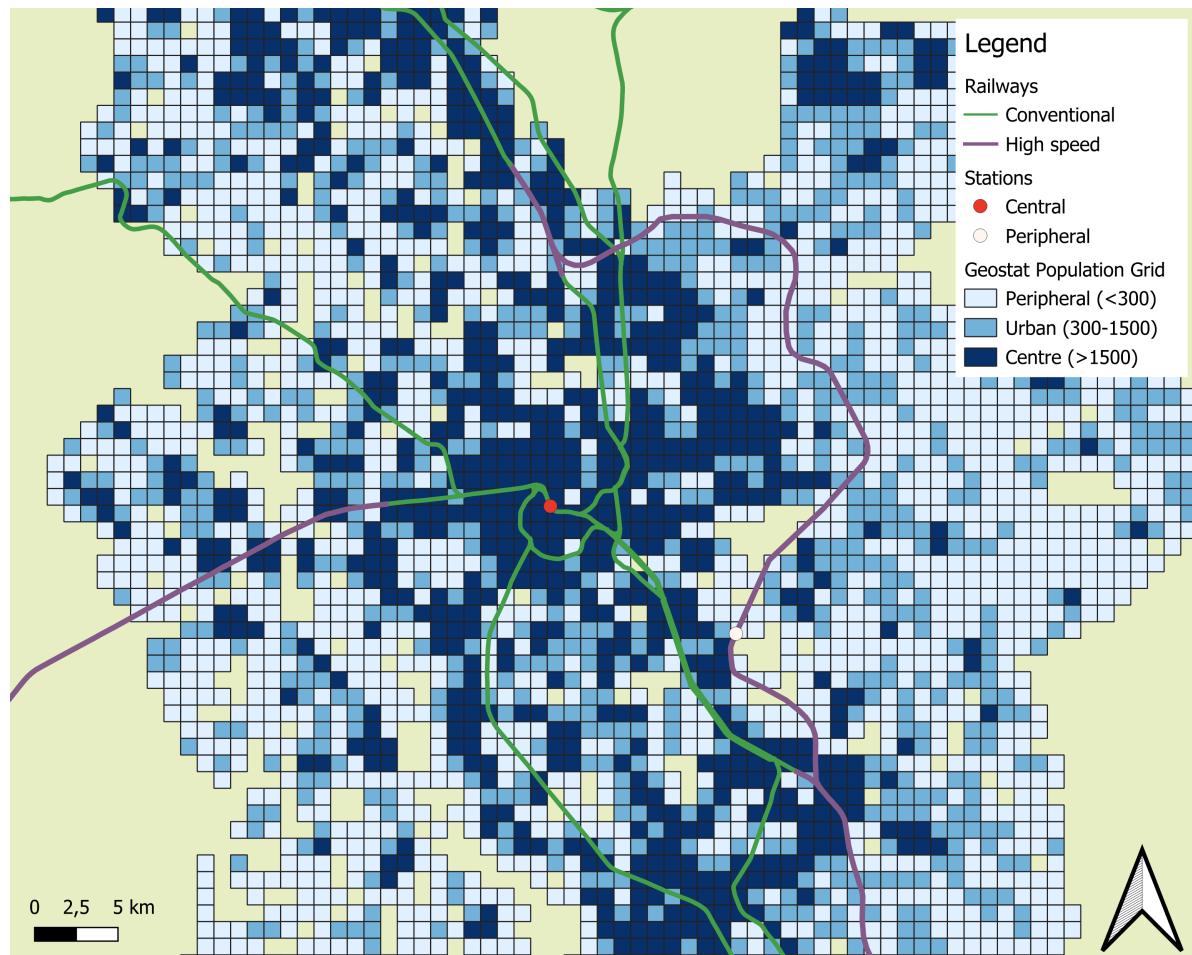


Figure 6.3: The adapted railway network for the Q3 Cologne experiment, illustrating a peripheral detour via Cologne Bonn Airport in the east and the population density map of Eurostat (2020a). Created in QGIS (2023).

Table 6.4: Passenger welfare effect results of experiment set Q3.

ID	City	$\sum$ CS Air [million €/year]	$\sum$ CS 2050; PO [million €/year]	$\sum$ CS 2050; Both [million €/year]	$\sum$ CS 2024; PO [million €/year]	$\sum$ CS 2024; Both [million €/year]
Q3.1	Amsterdam	n/a	115	68	41	25
Q3.2	Budapest	47	43	66	15	24
Q3.3	Cologne	n/a	n/a	30	n/a	11
Q3.4	Lille	0	514	492	185	178
Q3.5	London	n/a	n/a	-235	n/a	-85
Q3.6	Stuttgart	3	-37	12	-13	4

The large variances in the result of $\sum$ CS Air, i.e. the benefits of the improved airport accessibility, can be explained in the following way:

- Budapest Liszt Ferenc International Airport is one of the two Hungarian airports that were selected for this thesis, see Figure 4.11. It is the largest airport in Hungary in passenger traffic (Eurostat, 2023) and in connections, having 70 connections, while the other Hungarian airport (Debrecen International Airport) has only 14 connections (Grolle et al., 2024). No other airports except these two are located near Budapest, which means that almost all air passengers that travel to or from Budapest take this airport. Adding to this that Budapest is located relatively on the eastern end of the HSR-network, far from many major destinations, makes that we expect high air passenger volumes from Budapest city to Budapest airport. The result of this is that the accessibility improvement produces substantial welfare effects for Budapest in Table 6.4.
- Stuttgart airport has a comparable number of connections (57), yet yields less consumer surplus. A substantial cause of this is the relatively small improvement in access/egress time, with only 2.5 minutes, where Budapest's accessibility improved with 7.6 minutes. The relatively small benefit is likely due to the fact that rail travel is a better option in western Europe due to the extensive HSR network there. In addition, Figure 4.15 has shown that rail is estimated to be dominant on trips from 300 to 1200 kilometres, and most destinations in Europe can be reached within that range from Stuttgart. This makes an improvement in the utility of air less impactful.
- The same is true for Lille as for Stuttgart, but then even more extreme. Lille is very well connected through the HSR-network and a lot of the demand is located in Western Europe in the passenger distribution matrix. Since rail is dominant on many OD-pairs, improving airport accessibility is relatively non-impactful. Rounded to millions, it does not produce a non-zero consumer surplus.

Since air travel is more dominant today, the expected benefits to passenger welfare are expected to be higher than estimated in this chapter.

The concept of the peripheral only (PO) scenario has been discussed previously in the analysis of the Q2 experiments, but there are also some remarkable results concerning the PO scenario here. 'peripheral only' can be a good policy decision, but then the peripheral station has to be easily accessible from every existing railway line that nears the city. An alternative is that there are multiple 'peripheral only' stations, like in the case of Paris. This precondition was not satisfied for Brussels in Q2 or Stuttgart in Q3, therefore leading to a very negative 'peripheral only' result.

How the results of Q2 and Q3 compare can be found in Appendix D. This appendix also contains all of the constructed network maps for the Q3 airport iterations.

6.4. Strategic relocation for passenger welfare

This section generates a large set of experiment results that are valuable for analysing trends in HSR-service relocation. It runs experiments for every bottleneck from chapter 5 in a variation of 2 to 8 experiments per city. These experiments are labelled after the four cardinal wind directions (N, E, S, W) and the four intercardinal wind directions (NE, SE, SW, NW).

The strategic allocation experiment was included in this study since it allows for more variation in the network-lay-out than, for example, relocating only along a currently existing line, leading to useful results. Results from multiple experiments around the same city also allow for the identification

of favourable and unfavourable HSR-network designs. Therefore, providing valuable input for sub-question 5, which aims to identify trends in the passenger welfare effect results. The downside of generating stations that are not located along existing or planned edges of the TEN-T network is that these routes had to be constructed manually in QGIS, which is labour intensive.

The first step in generating these experiments was to determine which locations would be selected. It was decided that the solution space for locating peripheral stations would be the range from -2km to +4km of the convex space of the GHS urban core (OECD, 2023). The argumentation for this is as follows: The GHS urban core (OECD, 2023) is the area for which section 4.2 defined that the average speeds of trains cannot exceed those of conventional trains, being 130 km/h. To ensure that experimental detours are created where high speeds can be maintained, they must be located outside of this urban core. Every edge outside of the convex form of the GHS urban core is, therefore, automatically able to be defined as high speed (OECD, 2023). However, if possible, it is more effective to locate peripheral stations closer to the city to decrease the access/egress times of OD-passengers. For this reason, the continuous range was created from -2 km of the convex urban core to +4 km. This range is not only used as a range in which stations can be located, it is also the solution space for constructing the HSR-detours.

The solution space for selecting peripheral stations is set through the defined convex urban core-based boundaries; it is, however, preferred to do locate stations as close as possible to the city within that boundary. This minimises the access/egress time for OD-passengers. Although the constraint for a peripheral station is still that it must be located in a peripheral area. The approach was, therefore, to select within the solution space the centre of the squared peripheral km which is closest to the city. To ensure that it is feasible to create a network from and to a through station, the selected grid cell must be surrounded by at least two peripheral cells, as has been put forward in the criteria for selecting HSR-station locations in section 6.3. The constraint that the station has to be located outside of the GHS urban core also applies for Q4.

An example result of the described procedure is provided in Figure 6.4, which contains alternative experiments for 7 wind directions. The selected stations per wind direction per city can be found with the corresponding results in Appendix D.

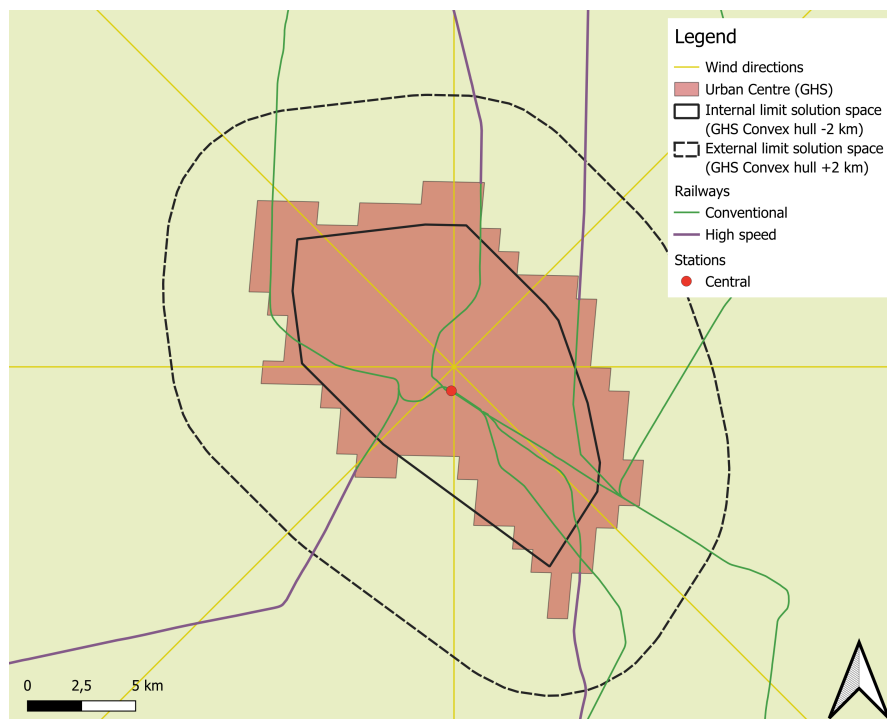


Figure 6.4: Solution space for Q4 experiment set creation in Mannheim.

The approach of path construction is mostly the same for Q4 as it was for Q3. The same objective O1, procedural steps P1, P2 and P3 and exceptions E1 and E2 still apply. However, three new constraints are defined for Q4 to limit the number of iterations and remove those that would not add to beneficial passenger welfare effects:

- C1 Peripheral station options that are located between two HS-railways that are heading in the same direction (<5 degrees difference over 50 km) are deleted.
- C2 The route through the city outskirts may not take longer than the city route (including accounting for speeds). This constraint was verified by extracting the distances of the urban route and the minimal peripheral detour from QGIS, and comparing these while accounting for the speeds. The argument for including this constraint is that the utility becomes, per definition, more negative if this constraint is not met, and thus that the experiment alternative would never lead to benefits.
- C3 The generated HSR-detour must be fully within the -2km to +4km range of the GHS urban core convex area (OECD, 2023).

Applying these constraints generated the total set of experiments as presented in Table 6.5. Cells containing C1 or C2 are deleted on the basis of that specific constraint.

Table 6.5: Experiment selection after filtration with constraint C1 and C2.

ID	City	N	NE	E	SE	S	SW	W	NW
Q4.1	Amsterdam	C2	C2	C2	C2	Yes	Yes	C2	C2
Q4.2	Brussels	No	Yes	Yes	Yes	No	Yes	No	Yes
Q4.3	Budapest	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Q4.4	Cologne	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Q4.5	Florence	Yes	Yes	No	No	C2	C2	No	C2
Q4.6	Frankfurt am Main	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Q4.7	Lille	C2	No	C2	C2	Yes	Yes	Yes	C2
Q4.8	London	Yes	Yes	Yes	Yes	Yes	Yes	Yes	C1
Q4.9	Mannheim	Yes	C1	Yes	Yes	Yes	Yes	Yes	Yes
Q4.10	Paris	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Q4.11	Stuttgart	C2	C2	C2	C2	No	Yes	Yes	Yes

The procedure for manual creation of the peripheral HSR-detours in QGIS was elaborated on in the section 6.3. A difference with the Q3 experiments of section 6.3 is that this section only performed experiments in the category 'Both', meaning that both central and peripheral stations exist in the experimental runs of the transport model. This was done to limit the amount of experiments, and since the other option, 'Peripheral only', more often leads to negative results for passenger welfare. Applying the 'Both' scenario provides, on itself, a result that is interpretable as the potential added value of a peripheral station if services are near-optimal from a passenger perspective. While 'Peripheral only' includes the (mostly) negative effects of relocating access/egress passengers away from the city centre. In addition, the 'Peripheral only' situation is expected to also be less realistic since it does not occur in the entire urban node selection, while the 'Both' situation occurs in 9 situations (see Q2). For these reasons, Q4 was only executed for the 'Both' scenario.

The experimental networks and complete set of results are provided in Appendix D. Both the results and the experimental network designs are labelled with the city name, experiment type and wind direction. The experiments that generated the highest passenger welfare benefits are provided in Table 6.6.

The two experiment results of Amsterdam are excluded from Table 6.6, which contains the best performing experiments. This was done since both station iterations cannot be defined as strategic allocations, which is essentially the goal of this section and Q4. Their results are negative since the access/egress times of the experimental stations are relatively high. The bypass itself exists for more than half of its length out of conventional rail, which does not allow for a faster speed on the peripheral route than on

the urban route. In addition, only a minority of traversing passengers pass through the urban area of Amsterdam since it is in a corner of the continental HSR-network. This means that not many passengers would benefit from a detour, if it had been faster. To be precise, more than 70% of the passenger flow in the Amsterdam area consists of OD-passengers.

Table 6.6: Passenger welfare effect results of best performing Q4 experiments.

ID	City	$\sum$ CS 2050; Both [million €/year]	$\sum$ CS 2024; Both [million €/year]
Q4.2	Brussels SE	117	42
Q4.3	Budapest S	58	21
Q4.4	Cologne W	209	75
Q4.5	Florence N	172	62
Q4.6	Frankfurt Am Main S	190	69
Q4.7	Lille S	552	199
Q4.8	London SE	152	55
Q4.9	Mannheim E	320	115
Q4.10	Paris E	431	156
Q4.11	Stuttgart W	44	16

6.5. Analysis of the results

This section aims to define a number of trends from the results. It begins with an exploration of possible performance metrics that appear to improve passenger welfare. Subsequently, it addresses conditions in which relocating HSR-stations to a peripheral area might be particularly advantageous. The section concludes with a visual diagram that illustrates both advantageous and unfavourable network configurations.

Three performance indicators were hypothesised to be beneficial to the potential of passenger welfare benefits. These three are expected to apply to any situation where a peripheral HSR-station is realised in a hypothetical town where there is also a centrally-located HSR-station with the shortest access/egress time, with services existing to both of them. The three hypothesised performance indicators that are expected to scale with the passenger welfare benefits are the following:

1. The number of traversing passengers that might benefit from a peripheral detour;
2. Ratio between the in-vehicle time of the urban route and the in-vehicle time of peripheral route;
3. Ratio between the distance of the urban route and the distance of the peripheral route.

Only three performance indicators are hypothesised for the 'Both' experiments. However, two other ones are hypothesised to apply for the 'peripheral only' (PO) experiments, namely the ratio between the access/egress time of the urban station and that of the peripheral station, and the ratio between the number of traversing passengers and the number of OD-passengers. These two indicators are expected since there is an explicit trade-off in that scenario that determines whether there are welfare benefits or losses, originating from the fact that OD-passengers are expected to experience an increase of access/egress time while traversing passengers are expected to experience a decrease of in-vehicle time. These two effects provide opposite effects, with the first one leading respectively to negative passenger welfare effects and the second one leading to positive welfare effects. In other words, there is an important trade-off in the OP scenario. The two hypothesised performance indicators for OP were not tested in the analysis for this section since the majority of the experiments in this chapter were done in accordance to the 'Both' scenario to check for the near-maximum positive welfare effects.

A scatter plot was created to check for a correlation between the number of traversing-passengers and the consumer surplus of a 'Both' experiment. To isolate this effect, only comparable experiments were selected. Comparable in this case means that they all are an experiment of the category 'Both' with positive welfare effects, and that the effect of adding one peripheral HSR-station in the outskirts is tested. This second constraint was established to ensure that no other peripheral stations exist in the $t = 0$ scenario that might distort the comparison. If multiple experiments of the same city exist, the

one with the highest result was included. Basically, the generated set contains only experiments that generate substantial passenger welfare benefits through the addition of one peripheral station. This set contains: Birmingham Q2; Budapest S Q4; Cologne W Q4; Copenhagen Q2; Florence N Q4; Frankfurt Am Main Q2; Lille S Q4; London SE Q4; Lyon Q2; Mannheim E Q4; Montpellier Q2; Stuttgart W Q4. The resulting scatter plot is provided Figure 6.5.

The traversing passenger volumes per city were generated by running an iteration of the transport model with only one central station per urban area for these 12 cities. The only station present per area then contains all of the traversing passengers that pass through the area of the urban node (FUA). These 12 values on traversing passenger flows were then used to plot against the passenger welfare benefits of the 12 listed experiments.

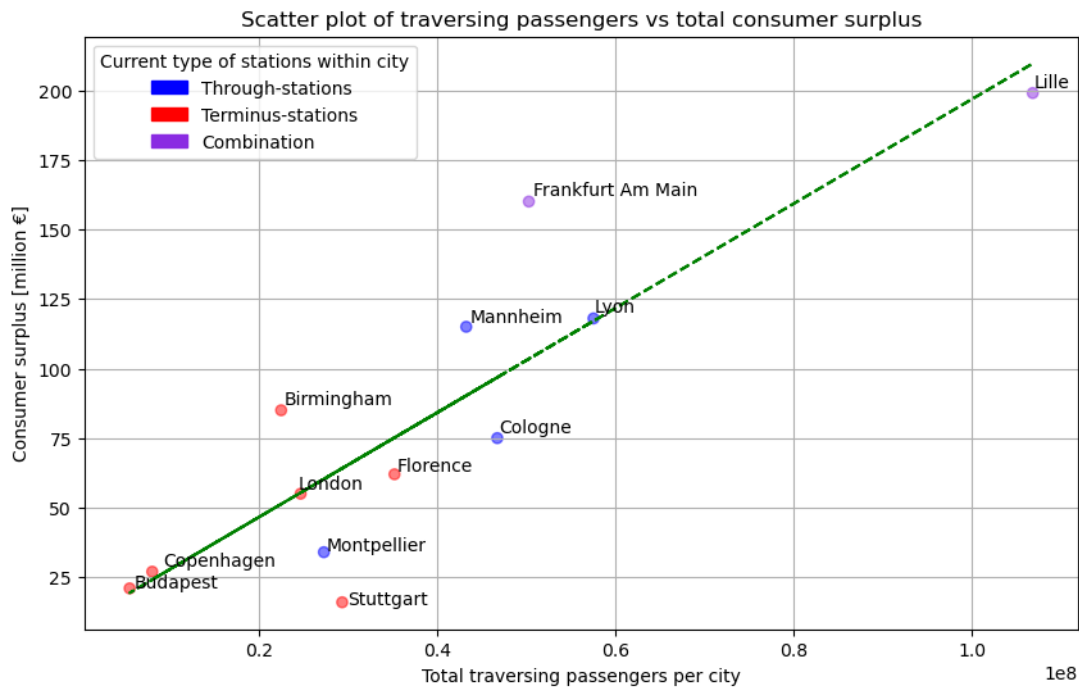


Figure 6.5: Scatter plot between traversing passenger volumes and consumer surplus [€] generated by peripheral station.

Statistical analysis indicates a strong and significant positive relationship between the number of traversing passengers and the consumer surplus, providing a high Goodness of Fit value ($R^2 = 0.76$) and a high Pearson correlation coefficient (0.87), but these results should be interpreted cautiously due to the small sample size of 12. The deviations from the regression line are expected to arise from the two other indicators, since the added value of the peripheral HSR-detour deviates strongly between experiments.

This first indicator, which is the number of traversing passengers, is also illustrated visually by the peripheral stations of Birmingham and Lyon. Figure 6.1 and Figure 6.2. These figures show that there are relatively high amounts of traversing passengers. The number of traversing passenger is even sufficiently high enough to lead to welfare benefits in the peripheral only (PO) scenario, and that while the access/egress times of the peripheral stations are substantially lower than their centrally-located counterparts.

The other two performance indicators, concerning in-vehicle time (2) and distance (3) were not statistically checked for correlation as no data on them was collected during the experimental phase, but the results suggest that they scale with them. Comparison of, for example, Figure D.39 and Figure D.40 illustrates the beneficial effect of indicator 2, being the ratio between in-vehicle time of the urban route and the in-vehicle time of the peripheral route. In both the base scenario and the Florence N scenario,

the distance of both routes is approximately the same. However, the speed is higher on the peripheral route, generating substantial passenger welfare effects as illustrated in Table 6.6. Indicators 2 and 3 also directly correspond to the attributes in the utility function.

Lastly, two additional elements impact the passenger welfare results that were not expected to play a substantial role in the 'Both' scenario. This concerns the access/egress time of the peripheral station and the number of OD-passengers. It was expected that the access/egress times of the peripheral stations would be higher than those of their urban counterparts, and therefore that OD-passengers would prefer the urban station and that the access/egress time of the peripheral station would not impact the results much. The access/egress method of this thesis did however lead to several experiments where the access/egress time of the peripheral station is shorter than that of the urban station, leading to higher passenger welfare benefits. The impact of this is elaborated on in section 7.2.

In addition to the performance indicators, some conditions were identified that seem to enhance the potential of passenger welfare benefits of peripheral HSR-stations. These effects have not been isolated or statistically verified, since the relevant examples are too few in number and too different in network layout, but they are illustrated in the results and align with the applied methods of this thesis. The following three beneficial conditions have been identified:

- Relocating high-speed services from a terminus station to a peripheral through station can amplify the potential welfare effects. This potential is caused by the existing urban route, which includes a bidirectional track located in front of a terminus station. This bidirectional track can be skipped twice when a peripheral detour is realised. In addition, turnaround times at such stations are relatively high, although they have not been included in the transport model. Examples of bottleneck city experiments with such terminus stations and beneficial effects are Florence, Birmingham, and Stuttgart.
- Another condition that yields potentially high welfare benefits is when inner-city transfers are necessary between HSR-stations for traversing a city. This situation is the case for Budapest, London and Paris. The results have shown that this can lead to significant passenger welfare benefits, especially for Paris but also to a lesser extent for Budapest and London. The latter two generate comparable benefits per passenger when taking into account their respective number of traversing passengers, as visualised in Figure 6.5. It is hypothesised that Paris benefits most out of these three, since the inner-city transfers are the longest, varying from 5 to 8 km, while Budapest has transfer distances of 2 to 4 km, and London has transfer distances of lower than 1 kilometre. In other words, most of the benefit of a peripheral detour was to be gained for the case of Paris.
- The last condition is that an airport is located in a location that is also strategic for the HSR-network. If this is the case, the allocation of an HSR-station at the airport can lead to substantial benefits for passengers of both modes. Although only three Q3 experiments have been performed that contain increased airport accessibility, they indicate that this could in fact lead to higher passenger welfare benefits for both train and plane passengers. The results and the literature suggest that HSR stations in airports can lead to amplified passenger welfare benefits (Voltes-Dorta and Becker, 2018). However, due to the small sample of experiments, more research is needed to confirm this.

The last segment of this section concerns which network designs of peripheral HSR-stations are advantageous for passenger welfare benefits and which are unfavourable. Figure 6.6 presents in the upper half a series of situations in which the allocation of the HSR-station is advantageous for passenger welfare. They are discussed from left (1A) to right (4A).

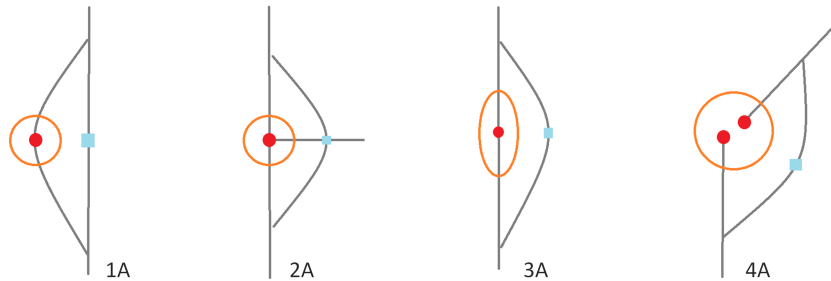
- 1A resembles the situation of Birmingham (Q2) and Montpellier (Q2). For this elaboration, we assume Birmingham as depicted in Figure D.1. As one travels from north to south, or the other way around, stopping at the centrally-located Birmingham Curzon Street is an unnecessary urban detour. Stopping at Birmingham Interchange, on the other hand, is both a faster route and a shorter distance. In conclusion, scenario 1A describes an urban core that leads to a detour to either the left or the right side of a shortest high-speed path. Substantial welfare effects can be acquired by constructing a peripheral high-speed station according to situation 1A.

- 2A The second figure illustrates where a station is advised to be located in a T-shaped HSR network. This advantageous design is grounded in the results of Cologne S (Q4), but also Frankfurt Am Main S (Q4) and Lille S (Q4). These results show that locating a station close to the long side of the T can lead to high passenger welfare benefits. A counterexample that is also T-shaped, but unlike 2A, is provided by Frankfurt Am Main SW (Q4) in Figure D.46. This design illustrates a station that is further away from the long end of the T, creating less-effective paths and less positive welfare effects.
- 3A In the case of a relatively long-shaped urban area, there is a relatively long section of the urban railway in which speeds are assumed to be lower. If this is the case, the potential benefit of maintaining high speeds in the city outskirts is higher. Examples that resemble 3A are Brussels SE (Q4) and Mannheim E (Q4), respectively in Figure D.22 and Figure D.60.
- 4A Closing off the list of advantageous designs is the previously discussed condition of a city with multiple terminus stations, with Budapest S (Q4), London S (Q4) and Paris (Q2) as examples.

The unfavourable designs, the lower half of Figure 6.6, require less explanation since they are quite intuitive and frequent in the results of Appendix D. Note that these designs might lead to positive passenger welfare benefits, if traversing passengers experience sufficient utility improvement, but they do not nearly realise the potential of passenger welfare benefits like 1A, 2A, 3A and 4A do.

1U is expected to only provide negative welfare effects, as it has a much longer travel distance and a comparable in-vehicle time. Examples of 2U are frequent in this research, including the Q4 experiments of Frankfurt Am Main N and NE, and Cologne E and NE. All four examples lead to negative or limited positive welfare effects. The disadvantage of 3U is that the peripheral station is located relatively far away from the population in the catchment area, which is especially a problem since the city is stretched in that direction, leading to very high access/egress times. The disadvantage of 4U has been described before in the context of Budapest, London and Paris.

Advantageous rail network
designs for passenger welfare



Unfavourable rail network
designs for passenger welfare

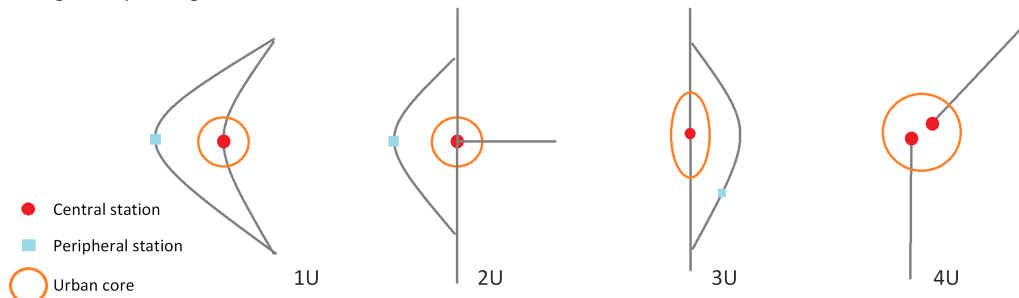


Figure 6.6: Identified trends in the passenger welfare effect results.

6.6. Passenger welfare effects in the context of SCBA

This section aims to put the monetary passenger welfare effects in the perspective of economic appraisal. It does so by discussing its relevance in the context of Social Cost Benefit Analyses (SCBA), which allows for answering Q6.

SCBA is an economic appraisal method which has been applied in the assessment of railway infrastructure through many literature sources of chapter 2 (Bröcker, Korzhenevych, and Schürmann, 2010; Adler, Pels, and Nash, 2010 Proost et al., 2014). However, it is used not only in the literature to estimate the efficiency of infrastructure investments, but also by governmental organisations like the EU (European Commission, 2014) and the Dutch government (Ministry of Finance of The Netherlands, 2020). European Court of Auditors (2018b) describe the use of SCBA in the HSR-context in the following way:

”As high-speed lines are expensive investments, it is crucial to correctly analyse all major costs and benefits upfront before deciding whether or not to build. When used correctly, cost-benefit analyses (CBAs) make it possible to assess a project’s social return on investment and its social desirability and usefulness before any decision is taken.”

How such ‘contributions to social welfare’ are assessed is illustrated both by an analysis paper on SCBA in the context of high-speed rail stations at airports (Widmer and Hidber, 2000) and by the SCBA Guide of the EU (European Commission, 2014). Both (Widmer and Hidber, 2000) and (European Commission, 2014) group the costs and benefits of such analyses into four categories:

- A Investments
- B Producer surplus
- C User surplus (i.e. consumer surplus)
- D Externalities

The results of this thesis fit in the second to last category, otherwise mentioned as consumer surplus. Widmer and Hidber (2000) state that the consumer surplus is often the most important benefit in analyses on railway investments. A conclusion which Widmer and Hidber (2000) derive from performing SCBAs for five railway stations at airports.

The research carried out by Widmer and Hidber (2000) mainly examines the advantages of improved airport accessibility. In the process, it uncovers and asserts that substantial benefits for rail passengers can be achieved by rerouting HSR-services via airports, specifically in the context of long-distance rail travel through Charles de Gaulle (CDG) airport. Widmer and Hidber (2000) identify that the users’ benefit from creating the Paris CDG high-speed railway station is ‘impressive’ since it provides a peripheral bypass, therefore not needing to use inner-city transfers from Gare du Nord to Gare de Lyon, for example. In doing so, Widmer and Hidber (2000) add to the findings of this research that peripheral HSR-detours can lead to substantial passenger welfare benefits. It is, as far as known, the only paper that estimates, in addition to this thesis, the quantitative effects of passenger welfare of a peripheral HSR-station with corresponding detour.

The described SCBA for the Paris Charles de Gaulle case is examined in this section to review whether the results of this thesis would be substantial in such an appraisal, especially in comparison to the investment costs. This case was selected over the other four cases of Widmer and Hidber (2000) since it reflects the context of this thesis, concerning the construction of an HSR-station that provides a peripheral detour around the city. NB: A major difference to this research is that Widmer and Hidber (2000) evaluates only passengers who have to travel from or to the Charles de Gaulle airport in Paris, and had previously had to travel from the centre of Paris to the airport by underground or taxi. The producer surplus, user surplus, and externalities are derived from this group of passengers.

Table 6.7 shows the resulting SCBA from Widmer and Hidber (2000), concerning only ‘those rail passengers having the airport as rail destination or origin’. Note that the values are for the entire period of economic life of the infrastructure, which is the station and accessory rail. This is a standard procedure for SCBA, where all cash flows related to the operations during the project lifetime are assessed (European Commission, 2014). A discount factor of 4% was applied for uprating the monetary values.

This value of 4% was applied in both the report of Widmer and Hidber (2000) itself and in this thesis, thus providing consistency. Since the data per year from 1997 is in French Francs (FF), they were first uprated to 1999, then transferred to € and then uprated to 2024. The applied €/Franc exchange rate was 1 € for 6.55 FF (American Numismatic Society, 2024).

Table 6.7: SCBA results for the TGV Charles de Gaulle station from (Widmer and Hidber, 2000). NB: The results are derived from rail passengers that specifically have the airport as origin or destination.

Cat.	Description	Million FF 1997	Million € 2024
A	Investment costs	-2043.5	-899.6
B	Saldo revenues (rail operator)	2817.4	1240.2
	Effects on rail transport	773.9	340.7
B	Saldo revenues - costs (other operators)	-1257.7	-553.6
	Effects on public transport	-483.8	-213.0
C	Users' benefit	1839.2	809.6
D	Avoided external effects	530.0	233.3
	Effects on national economy	1885.3	829.9

The uprated investment costs of Table 6.7 are about 900 million € for the station and corresponding infrastructure. Comparing this with passenger welfare costs as calculated for the Charles de Gaulle TGV station in combination with Marne-la-Vallée-Chessy in Q2, being between 334 and 296 million € per year for 2050, illustrates that the results from this research can be very impactful in effectuating a positive benefit-cost ratio of more than 1.

The expected reason for the difference in consumer surplus (category C), which is only 809.6 million € for the entire life span according to Widmer and Hidber (2000), while those found in this research are between 334 and 296 million € per year, is found in the fact that Widmer and Hidber (2000) evaluates only the rail passengers that have as origin or destination the airport, while this thesis assumes all long-distance passengers that might pass it per year. The results of category B (producer surplus) and D (externalities) are therefore also not directly comparable, but it is notable that they are both positive as a result of the construction of the TGV Charles de Gaulle Station.

In conclusion, the orders of magnitudes of the estimated passenger welfare effects of this chapter are comparable to those of a sample HSR-station cost-benefit analysis. Therefore, realistic and expected to have the potential to effectuate positive benefit-cost ratios in SCBAs.

6.7. Limitations of the welfare experiments

This section continues the identification of research assumptions in the style of chapter 4. Therefore first describing relevant assumptions and their impacts, and then providing a table with the estimated size of the impacts and the corresponding likeliness that the assumption is an oversimplification of reality. The assumptions are described in approximately the order in which they have been applied in this chapter. The overview is provided at the end of the chapter in Table 6.8.

- A37 The assumption was made that the induced passengers start travelling by rail at least couple of years prior to the station infrastructure change, that is simulated in the experiments, for the year of 2050. However, in reality, they will probably be generated much earlier than a couple of years before 2050. Many of the planned railways are scheduled to be constructed before 2030 or before 2040, as can be seen in Appendix A, which would mean that the induced demand passengers will be generated much earlier than 2050. If that is the case, these values would experience autonomous growth as well, which would lead to a total number of passengers in 2050, and therefore other passenger welfare effects. The potential growth is assumed to be limited to some extra percentages since induced demand is assumed to be 20% of the total demand a couple of years after introduction. The impact on the results is therefore considered medium. The likeliness of oversimplification is however high.
- A38 Another assumption concerning the induced demand is that they are expected to continue travelling long-distances purely by train, and therefore receiving the full effects of the railway infras-

structure changes. Intuitively, this does not seem very likely. On the other hand, literature does state that 20% of demand for new HSR consists of induced demand even after numerous years of operation. It is concluded that the modelling assumption that they cannot switch long-distance mode is highly impactful, especially since it would estimate the rail mode and the passenger welfare benefits. The likelihood of oversimplification is estimated to be low, since the approach does, however, fit the literature.

- A39 This thesis has taken into account the induced demand effects that are expected when realising the Comprehensive TEN-T, an effect of the construction of new railways in Europe. It has however not taken into account additional induced demand effects when realising a new station and the corresponding infrastructure in Q3 and Q4. This implies that the expected user benefits are higher than currently modelled. When including these additional benefits, one should take into account that the rule-of-half must be applied to user benefits of this group of switchers. Quantitatively, this would mean that some years after construction of the peripheral detour, demand would have grown there with 25% from the modelled situation for 2050. Applying the rule-of-half would imply that the passenger welfare results could be approximately 12.5% higher than they are currently estimated.
- A40 Both Q3 and Q4 presuppose that commuter rail services continue to operate from the centrally-located stations. The reasoning for this assumption was twofold. In the first place, the stations in Q2 that illustrate real-world rail network systems all contain at least one peripheral and one central station. Secondly, literature has described that relocating these services to the city outskirts would negatively impact daily commuters (Kowalski, Marada, and Chmelfk, 2023). This assumption has a high impact for the peripheral HSR-station design, namely that the focus on access/egress time minimisation is less urgent than if these commuters would use the new peripheral station. In addition, this constraint provides the possibility of positive passenger welfare benefits. If daily commuters would have to travel long access/egress distance on their relatively short trips, the passenger welfare effects would presumably become negative. In conclusion, the impact of this assumption is high, but the likelihood of oversimplification is low since the cities of experiment Q2 all still use their centrally-located stations.
- A41 The network design of the peripheral detours was manually delineated in QGIS (2023) through visual approximation of realistic curvature. This approach was however not constrained by limitations like the maximum allowable curve per unit of distance. This manual approach might have led to either too positively designed detours or designs that were too cautious in its creation of curves, which would lead to respectively more positive and less positive welfare effect results.
- A42 The approach in which the detour paths have been constructed for the experiments is prone to human error. The results are, however, as was expected with the hypothesis, so no distinct errors are present. It is however expected that small errors are present when it concerns manual edge cuts or updated distances. This chance at human errors is high since the experimental process required many manual redesigns of the network in QGIS (2023).
- A43 The aim of this chapter was to create experimental HSR-stations with peripheral detours, while assuming that this can be created within the -2km to +4km convex area of the GHS urban core. A main limitation of the solution space is that it does not prevent the detours from passing through populated areas. In a few cases, like Brussels, the detours had to pass through many urban areas, see section 1.7 for the definition. While in other cases, the solution space was located relatively far away. The prime example of this is London, which has relatively many Q4 experiments with negative passenger welfare effects. This originates from the fact that the solution space was far away from the city, which leads to a welfare loss for the OD-passengers, which form a majority for London. In other words, this thesis explicitly aims for peripheral detours that provide welfare benefits, but they were not always feasible within the set solution space. In conclusion, applicance of the described solution space can both positively and negatively impact the passenger welfare results, and it does not always provide for a peripheral detour. The impact on the passenger welfare results is therefore assumed to be medium. The likeliness of oversimplification is assumed to be medium, since it does provide for peripheral detours in most cases and is realistically close to the city without passing through the urban core (OECD, 2023).
- A44 The detour creation procedure focuses only the avoidance of population density and airport infrastructure, which is a narrow approach that does not take into account other zoning plans. An example of this is the case of the Q3 experiment of HSR-service relocation to the airport of Cologne the

railway tracks move through a nature area called 'Wahner Heide im Rhein' (Google Inc., 2024). The described approach of peripheral detour creation might overestimate the passenger welfare results due to designing too short detours, but these effects are expected to be limited. This approach does, however, oversimplify reality strongly.

- A45 Peripheral stations are designed to provide the possibility to be used as throughput stations. but since edges in the Python model are bi-directional, this sometimes leads to stations that are used as terminus stations by some paths. For example in the very well performing Lille S experiment, see Figure D.49. A path is available there which would allow train that originate from the south, from Paris, to pass through the Lille S experimental station without switching direction, but the model enters and exits Lille S on the same side since it is the slightly faster option. It is therefore assumed that the model oversimplifies reality here, but that the impact is only limited since it concerns probably only a few minutes of time gain/loss.
- A46 'Both' is the most frequent experiment type that has been performed in this chapter. The disadvantage of the 'Both' scenario is however that it inherently assumes that unlimited services exist that supply every passenger with their preferred rail route, as has been discussed in section 6.2. This is too optimistic for reality, implying that the 'Both' scenario overestimates passenger welfare effects. The results of the 'Both' experiments can therefore not be interpreted as the likely passenger welfare effects, but as a near-maximum potential of welfare effects. Why it is near-maximum is described in section 6.2.

Table 6.8: Overview of assumptions of the passenger welfare analysis.

ID	Assumption	Impact of assumption	Likelihood of oversimplification
A37	Induced passengers start travelling by rail a couple of years prior to the station infrastructure change, which is simulated for 2050.	Medium	High
A38	Induced demand passengers will only take the train for long-distance trips.	High	Low
A39	Induced demand effects of the new peripheral HSR-stations and corresponding infrastructure in Q3 and Q4 are not considered.	High	High
A40	Commuter rail services operate only from and to centrally-located stations, they do not relocate to peripheral stations.	High	Low
A41	No geometric design constraints, for example on maximum curvature, have been applied. Peripheral detours were manually delineated in QGIS through visual approximation of realistic curvature.	Medium	High
A42	The detour path construction is prone to human error, with small errors expected in manual edge cuts or updated distances.	Low	Medium
A43	The solution space for peripheral HSR-detours is confined to -2km to +4km of the convex shape of the GHS urban core (OECD, 2023).	Medium	Medium
A44	Peripheral HSR-detour design only considers population density and airport infrastructure.	Low	High
A45	Peripheral stations are designed as through stations, but sometimes act as terminus stations in the model.	Medium	High
A46	The 'Both' experiment type assumes unlimited services, supplying every passenger with their preferred rail route.	High	High

Conclusion, Discussion & Recommendations

7.1. Conclusion

This thesis addresses the main research question:

To what extent, and under which conditions, can the relocation of high-speed rail services from centrally-located stations to city-outskirt stations lead to passenger welfare gains?

This question is explored through the lens of several sub-questions, which together provide the answer to this question. High-speed rail is abbreviated as HSR in both the questions and their corresponding answers.

Q1: Which centrally-located HSR-stations in the 2050 TEN-T network can be identified as potential bottlenecks based on forecast passenger volumes?

This thesis identifies, based on the application of a mode-route choice model in the context of European long-distance travel per 2050 and a saturation analysis, that 14 centrally-located HSR-stations are expected to become oversaturated per 2050. All 14 are therefore expected to exceed their commercial capacity, while others are expected to exceed even their theoretical capacity. This is shown visually in Figure 7.1. The oversaturation of these stations occurs on average for 38% due to long-distance rail travel, which originates from the choice model that was applied to the proposed Trans-European Network of the European Commission (2021b). The rest of the share is caused by commuter trains, which were mostly estimated on openly available data (Eurostat, 2024). It is therefore concluded that, in most cases, relocation of HSR-services could be sufficient to make the demand fall below the commercial capacity. This is under the assumption that commuter train services will remain visiting centrally-located stations, regardless of the long-distance services.

The 14 identified bottlenecks were identified out of a set of 94 centrally-located HSR-stations, of which 13 are located in Western Europe. This is not surprising, since most of the demand in the long-distance transport model is present in this part of the continent. The results suggest that terminus stations are facing a relatively high risk of oversaturation, since 9 out of 14 stations are terminus stations. This share of 64% is relatively high, since the general share of terminus stations is 36% in the evaluated set of 94 HSR-stations. In addition, 9 bottleneck stations were found to have opened in the 19th century. It is therefore hypothesised that the high train volumes in Western Europe originate from the fact that many old stations are located there, and that the railway network and the corresponding passenger volumes have evolved naturally around these stations.

Lastly, it was observed that these bottlenecks have a high average ratio of traversing passengers / origin-destination (OD) passengers of 3.9, while the total set of centrally-located HSR-stations has an average of 1.9. This result raised expectations on the potential welfare benefits of relocating HSR-

services away from these bottlenecks, since these benefits were expected to scale with the number of traversing passengers.

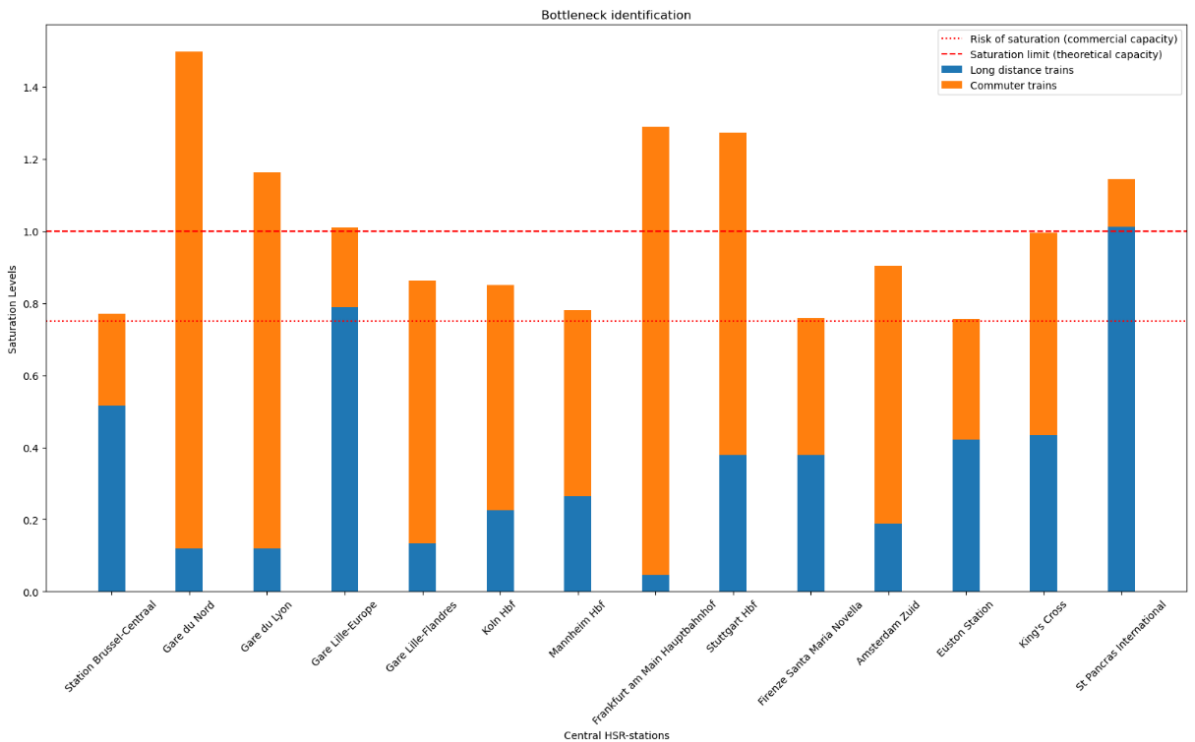


Figure 7.1: Bottleneck identification through saturation analysis. Adapted from Python (Python Software Foundation, 2024).

Q2: What is the potential of existing HSR-stations, which provide a detour in the city outskirts by 2050, to generate passenger welfare benefits?

This question provides context on the efficiency of existing peripheral stations that provide an HSR-detour in generating passenger welfare, in comparison to only having centrally-located stations. It was answered by running iterations of the previously mentioned transport model for different experiments, with different network settings, and comparing their results through the logsum-based approach with a base scenario in which only a centrally-located station exists. The results were generated for nine existing stations that comply with the description in the sub-question. These passenger welfare results, i.e. the summed consumer surplus (*CS*) results, are presented in Table 7.1. The results were generated for two types of experiments, one in which all long-distance services are relocated to the peripheral station, and one in which (unlimited) services are assigned to both the central and the peripheral stations. These types are referred to, throughout the answering of Q2, Q3 and Q4, as the 'Only Peripheral' (OP) and 'Both' scenarios. The results were initially generated in euros per 2050, since that is the prediction year of the transport model, and then discounted with the Net Present Value method to estimate their current expected social value. All of the peripheral detour results in Table 7.1 concern the passenger welfare effects as generated by one peripheral station, except Paris. This exception was made since there are two peripheral stations on the same detour, Charles de Gaulle Airport 2 TGV and Marne-la-Vallée-Chessy, which both were included in one experiment (Q2.8).

The results illustrate that substantial passenger welfare benefits are generated by these existing HSR-stations, with Table 7.1 providing the answer to the sub-question. Six of the nine experiments yield positive results, suggesting that these existing peripheral stations are allocated fairly to very strategically. Birmingham, Frankfurt Am Main, Lyon and Paris are thought to be located very strategically, not only because their results suggest so, but also because their network lay-outs illustrate that the peripheral detour can both be faster and shorter for many traversing passengers. In addition, the distinctively

high benefits for Paris are expected to originate from the fact that the urban route requires an inner-city transfer between railway stations, which amplifies the attractiveness of the peripheral detour.

Unexpectedly, Table 7.1 illustrates results where 'Only peripheral' is the most favourable. This suggests that the peripheral station is not only a better option for traversing passengers, aligning with the expectations of this thesis, but that is also preferred by OD-passengers. Examples of this phenomenon can be observed in Copenhagen, Frankfurt am Main, Montpellier, and Paris. The frequency of this result type implies that the access/egress speed approach overestimates the accessibility of peripheral stations. This was unexpected since one would intuitively assume that the OD-passengers are in general not fond of a station which is further away of the city. This matter is discussed further in the discussion part of this chapter, section 7.2.

It can be concluded from the negative results of Brussels, Vienna, and Leipzig that their corresponding peripheral stations do not provide detours that add value, but that they are only beneficial for serving the direct proximity of those stations, which is in these three cases an airport. The possibility that the logsum-based approach provides negative results is caused by the formulation of the transport model, in which a share of the passengers may choose a sub-optimal path when it exists.

Table 7.1: Passenger welfare effect results of experiment set Q2 in million €/year

ID	City	$\sum$ CS 2050; PO [million €/year]	$\sum$ CS 2050; Both [million €/year]	$\sum$ CS 2024; PO [million €/year]	$\sum$ CS 2024; Both [million €/year]
Q2.1	Birmingham	226	235	81	85
Q2.2	Brussels	-323	-32	-117	-12
Q2.3	Copenhagen	106	74	38	27
Q2.4	Frankfurt	517	443	187	160
Q2.5	Leipzig	-35	-4	-13	-2
Q2.6	Lyon	255	326	92	118
Q2.7	Montpellier	103	93	37	34
Q2.8	Paris	925	820	334	296
Q2.9	Vienna	-317	-55	-114	-20

Q3: What would be the passenger welfare effects of relocating HSR-services to an airport on the outskirts of a city, relative to maintaining them at stations with high centrality?

The results that answer Q3 are presented in Table 7.2, containing passenger welfare effects of relocating HSR-services from the predicted bottleneck stations to airports. The Q3 experiments provide a nuanced view of the passenger welfare effects of relocating high-speed rail (HSR) services to airports on the outskirts of cities. While some cities displayed substantial passenger welfare benefits, others showed negligible or even negative outcomes, like London and Stuttgart, underscoring that a peripheral HSR-station is only beneficial for the railway network if located strategically. In three cases airport accessibility effects were included in the passenger welfare effect quantification, being Budapest, Lille, and Stuttgart, which provided varying outcomes. The peripheral detours were constructed manually in QGIS (2023) to minimise construction in populated areas. The corresponding designs can be found in Appendix D.

Experiment Q3.3, which estimates passenger welfare effects that correspond to a hypothetical peripheral station at the Budapest Liszt Ferenc International Airport, illustrates a 'Both' scenario where the relocation of HSR services to the airport brought about improved accessibility of the airport and an increase in consumer surplus due to the rail network change. The passenger welfare effects due to improved airport accessibility arise from Budapest Airport's unique position as the major Hungarian airport, having high annual passenger volumes and relatively many flight legs to European destinations (70). The contrary is true for the cases of Lille and Stuttgart, in which zero to little passenger welfare benefits were found due to airport accessibility improvement. This is partially caused by the fact that these airports are smaller and provide fewer connections, but it originates mainly from the fact that rail travel is a better alternative for long-distance in Western Europe than in Eastern Europe. The higher market share for rail on the OD-pairs that contain Lille and Stuttgart make that an improvement in air

utility is relatively less impactful on the consumer surplus results.

Although only three Q3 experiments have been performed that contain increased airport accessibility, they suggest that such HSR-allocation could lead to higher passenger welfare benefits through both the train and aeroplane modes. Both these results and the literature review of this thesis imply that HSR-stations at airports can lead to amplified passenger welfare benefits. However, more research is needed to confirm this. Such research would be valuable, especially since the EU aims for multimodality in long-distance trips in the TEN-T policy.

NB: The described issue of accessibility overestimation for some experimental peripheral stations, from Q2, is applicable here for the HSR-station at Amsterdam Schiphol Airport. This experiment is not expected to yield positive results in reality, but it does provide positive results in Table 7.2. A shorter access/egress time for the peripheral alternative is also the case for Cologne, the other four are in line with expectations. See section 7.2 for discussion on this issue.

Table 7.2: Passenger welfare effect results of experiment Q3 in million €/year

ID	City	$\sum$ CS Air [million €/year]	$\sum$ CS 2050; PO [million €/year]	$\sum$ CS 2050; Both [million €/year]	$\sum$ CS 2024; PO [million €/year]	$\sum$ CS 2024; Both [million €/year]
Q3.1	Amsterdam	n/a	115	68	41	25
Q3.2	Budapest	47	43	66	15	24
Q3.3	Cologne	n/a	n/a	30	n/a	11
Q3.4	Lille	0	514	492	185	178
Q3.5	London	n/a	n/a	-235	n/a	-85
Q3.6	Stuttgart	3	-37	12	-13	4

Q4: What would be the passenger welfare effects of relocating HSR-services to a strategic city outskirts location that maximises passenger welfare, relative to maintaining them at a location with high centrality?

The results for answering Q4 are presented in Table 7.3, containing passenger welfare effects of relocating HSR-services from the predicted bottleneck stations to strategic locations around the city. These results were retrieved by executing HSR-station allocation experiments in all feasible wind directions of the city outskirts, and selecting the best performing ones. The letter coding after each city name represents an (inter-)cardinal wind direction, which were used to characterise the experiments. The associated infrastructure was designed in a similar way to Q3. These network layouts are provided in Appendix D, together with the full table of results for all feasible wind directions.

The findings underscore the potential for substantial welfare gains under specific conditions, which appear to be primarily the strategic location and the typology of the passengers. The prime example of a strategic allocation is Lille S, which is very effective in providing a faster and relatively not much longer bypass, while still being quite accessible from the catchment area. This last detail plays a minor but relevant role in the result of the 'Both' scenario, where unlimited services are assumed and passengers can select their preferred path. Since the transport model generates a minority of passengers that select suboptimal paths, it is of value that the station is allocated not too far from the city. Lastly, the result for Lille is not only very high due to its favourable network design, but also due to the fact that it has the highest value of traversing passengers of all the assessed bottlenecks.

Table 7.3 contains only the best performing experiments, but the experiments also generated many results that yield lower passenger welfare benefits, or even negative welfare effects. In conclusion, the experiments conducted in the answering of Q4 provide compelling evidence that strategic allocation of peripheral HSR-stations is essential in generating passenger welfare benefits, and that strategically located stations can yield tens to hundreds of millions of euros in passenger welfare benefits per year.

Table 7.3: List of cities with the highest $\sum$ CS 2024 values of the Q4 experiment.

ID	City	$\sum$ CS 2050; Both [million €/year]	$\sum$ CS 2024; Both [million €/year]
Q4.2	Brussels SE	117	42
Q4.3	Budapest S	58	21
Q4.4	Cologne W	209	75
Q4.5	Florence N	172	62
Q4.6	Frankfurt Am Main S	190	69
Q4.7	Lille S	552	199
Q4.8	London SE	152	55
Q4.9	Mannheim E	320	115
Q4.10	Paris E	431	156
Q4.11	Stuttgart W	44	16

Q5: Which conditions contribute to passenger welfare benefits of peripheral HSR-stations?

The analysis of the passenger welfare results reveals several conditions that substantially enhance passenger welfare when peripheral HSR stations are implemented. These conditions can be differentiated to performance indicators, specific conditions, and network configurations. These are discussed subsequently in this section, and thereby answer this question.

Three performance indicators have been identified to be beneficial to the potential of passenger welfare benefits, of which the first one was statistically checked and the latter two were confirmed based on visual analysis of the experiment results. The three indicators are relevant to scenarios in which a peripheral HSR station is constructed in a town that already has a centrally located HSR station with the quickest access and egress times, and services are provided to both stations. They concern:

1. The number of traversing passengers that might benefit from a peripheral detour;
2. Ratio between the in-vehicle time of the urban route and the in-vehicle time of peripheral route;
3. Ratio between the distance of the urban route and the distance of the peripheral route.

A scatter plot was generated to examine the relationship between the number of traversing passengers and the consumer surplus in an experiment. To isolate this effect, only similar experiments were chosen. Comparable in this case means that they all are an experiment of the category 'Both' with substantial positive welfare effects, and that the effect of realising one peripheral HSR-station in the outskirts is tested. If multiple experiments exist that fit this description, the one with the highest benefits was selected. The resulting scatter plot is provided Figure 7.2. Statistical analysis reveals a strong and significant positive relationship between the number of traversing passengers and the consumer surplus, providing a high Goodness of Fit value ($R^2 = 0.76$) and a high Pearson correlation coefficient (0.87), but these results should be interpreted cautiously due to the small sample size of 12.

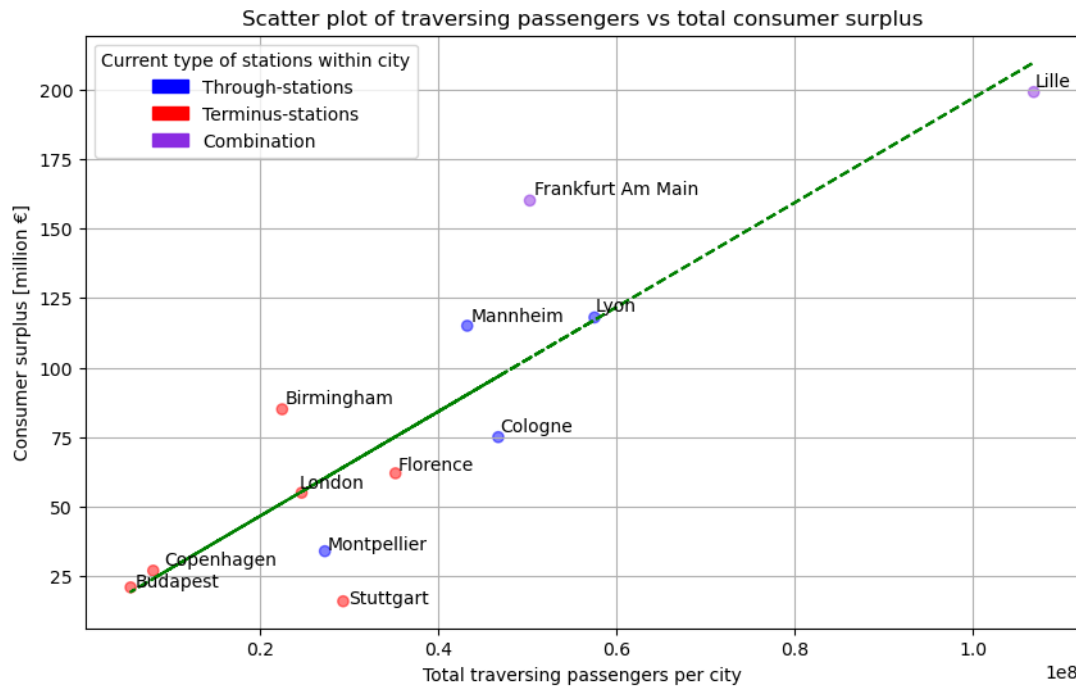


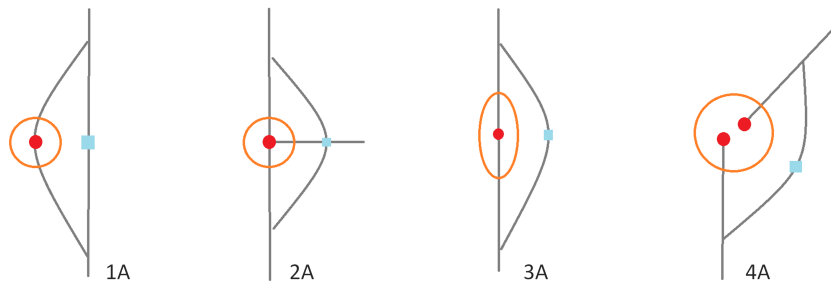
Figure 7.2: Scatter plot between traversing passenger volumes and consumer surplus generated by peripheral stations.

Some conditions have been identified that may enhance passenger welfare benefits at peripheral HSR-stations. While these effects haven't been isolated or statistically verified due to limited and diverse examples, they align with the methods of this thesis. Three beneficial conditions are highlighted:

- Relocating high-speed services from a terminus station to a peripheral through station can amplify the potential welfare effects. This potential is caused by the inefficiency on such an urban route, which includes a bidirectional track located in front of a terminus station. Examples include Florence, Birmingham, and Stuttgart.
- Another condition that yields potentially high welfare benefits is when inner-city transfers are necessary between HSR-stations for traversing a city. This situation is the case for Budapest, London and Paris. The results of these three cities suggest that the longer the inner-city transfer distance, the higher the potential welfare effects.
- The last condition that might amplify the welfare effects is when an airport is located in a location that is also strategic for the HSR network. As described in Q3; the allocation of an HSR-station at the airport can lead to substantial benefits for passengers of both modes.

As illustrated in Figure 7.3, the strategic location in coherence with the network configuration plays a vital role. These patterns were deduced from analysis of the best and worst scoring results, and align with the second and third performance indicators on travel time and travel distance. Examples of 1A include Birmingham (Q2) and Montpellier (Q2), examples of 2A include Frankfurt Am Main S (Q4) and Lille S (Q4), examples of 3A include Brussels SE (Q4) and Mannheim E (Q4), and examples of 4A include Budapest S (Q4), London S (Q4), and Paris (Q2).

Advantageous rail network
designs for passenger welfare



Unfavourable rail network
designs for passenger welfare

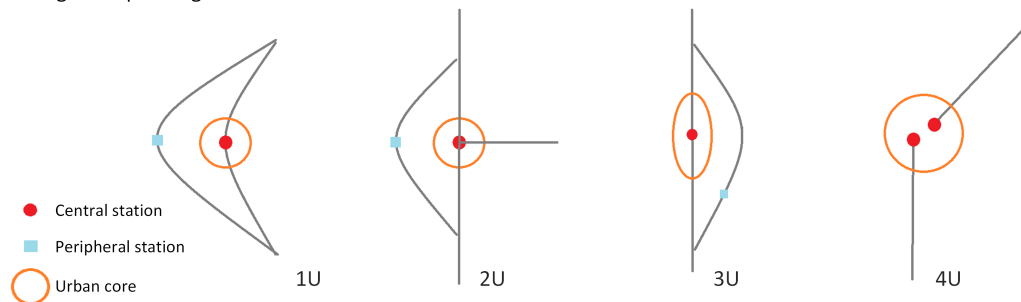


Figure 7.3: Identified trends in the passenger welfare effect results.

Q6: What is the relative size of the assessed passenger welfare effects in social cost-benefit analyses that appraise the construction of high-speed railway stations?

The analysis of passenger welfare effects, when compared to findings from the SCBA (social cost-benefit analysis) literature, confirms that the estimated magnitudes are realistic and potentially significant in economic evaluations of infrastructure projects. For example, the investment costs of the Charles de Gaulle HSR-station and associated infrastructure, uprated to today, are approximately €900 million during the project life-cycle. The annual consumer surplus estimated in this thesis is between €334 million and €296 million, as discounted from 2050. Both other categories of SCBA, producer surplus and externalities, were also benefits in the case of the Charles de Gaulle HSR-station.

Comparison with literature revealed that the passenger welfare effects are substantial in applicable cost-benefit analyses, suggesting that the relocation of HSR services from city centers to peripheral areas can play an essential role in effectuating positive benefit-cost ratios. This alignment underscores the potential of strategic HSR-service relocations from city centres to the outskirts.

Having discussed the answers to all sub-questions, this brings us to answering the main question.

In conclusion, the potential passenger welfare effects of relocating HSR-services from centrally-located stations to peripheral are substantial and conditions have been identified that contribute to the extent of these potential benefits. The estimated order of magnitude of these benefits to the European economy ranges from tens of million euros per year to a couple of hundred millions of euros per year, which is significant in the context of economic appraisals like social-cost benefit analyses. This order of magnitude of benefits can however also apply in the negative direction if either the allocation of the station is unfavourable or the corresponding network is not strategically designed. Examples of both advantageous and unfavourable designs are found in Figure 7.3. Essential performance indicators include sufficient traversing passengers that would experience the welfare benefits of a peripheral detour and a detour that is preferably faster (time) and shorter (distance) than the urban route. Finally, although being located in the city outskirts, a location that is in relatively close proximity is advisable in the context

of OD-passengers that might also use the peripheral station.

7.2. Discussion

This section discusses both major concerns to the concept of this thesis, thus concerning relocation of HSR-services to the city outskirts, and then discusses the most impactful assumptions that were made in generating the results. They are labelled in this section as 'General discussion' and 'Discussion on highly-impactful assumptions'.

7.2.1. General discussion

The goal of this subsection is to highlight four key issues and obstacles that concern the topic of this thesis.

1. Station allocation will in reality be based on more features than passenger welfare.

This research discusses the allocation of peripheral stations purely from a passenger welfare perspective. The only additional consideration that is consistent through all of the experiments is the aim for constructing the detours through peripheral area, i.e. areas with low population density. In reality, many more considerations would apply in station allocation. Roy and Maji (2022) describes the following features that should be taken into consideration: geographical features, topography, population distribution, and existing features, such as downtown location and transportation facilities. This list of features is comprehensive, but one essential feature is still excluded, being financial feasibility, which brings us to second topic of this discussion.

2. Although passenger welfare is expressed in monetary units, it is not a means of payment.

The synthesis of the literature study concluded that revenues are often not sufficient in providing a positive cost-benefit ratios (Hensher, 1997), and that this is why investments in high-speed rail are often defended on (passenger) welfare and environmental grounds (Jiao, Wang, and Jin, 2017). Such effects are included in SCBAs, which then provide a positive or negative social benefit-costs ratio. A positive social benefit-cost ratio substantiates that an HSR-investment is beneficial to society, but it does not provide means to invest. In other words, passenger welfare benefits can entail millions of euros, but it is not a cash flow that can be used to invest.

Adler, Pels, and Nash (2010) also describe that funding of HSR-infrastructure is high on the policy agenda. The research states that European HSR-infrastructure has generally been either fully funded by the government in question, or has been built under a public-private partnership with a government contribution. An example of such a public-private partnership applied to HSR-station Marne-La-Vallée-Chessy at Disneyland, where the Walt Disney Company contributed with €38.1 million of the total €126.5 million (Clavé, 2007). Another paper that describes that these projects can often not exist without funding is Kowalski, Marada, and Chmेलík (2023), which describes how the new Brno station is funded both nationally and internationally by the EU. The argument for the EU to fund this infrastructure project is that it concerns realisation of the TEN-T policy.

One can conclude that HSR-projects generally rely on funding to secure sufficient means for realisation of HSR. High passenger welfare benefits might contribute to positive social benefit-cost ratios, and this increases the chances of being funded by national governments and the EU, but passenger welfare benefits will never guarantee that infrastructure can be realised.

3. Local governments and residents are often opposed to peripheral stations.

Local governments and residents often resist the establishment of high-speed rail (HSR) stations on the outskirts of cities, preferring central locations that promise local economic and social benefits (Moyano and Dobruszkes, 2017; Hermelin and Gustafsson, 2022; Kowalski, Marada, and Chmेलík, 2023). A notable example is Lille, the third-largest city in France, which was initially proposed to have a peripheral HSR station to the southwest of Lille to reduce costs and shorten travel time between Paris and London (Moyano and Dobruszkes, 2017). However, local authorities advocated for a central station to create a new European business district around it, aiming for job creation and economic activities. This coalition of public and private stakeholders successfully influenced the decision to locate the HSR

station near the city center (Moyano and Dobruszkes, 2017). On a side note: This original proposal of locating a peripheral HSR-station in the southwest of Lille is remarkably close to the proposed strategic location for a peripheral station in Q4 of this research, and with the same goal of reducing travel times. This finding validates that the research suggests realistic allocations from a passenger efficiency perspective.

Similarly, in Liège, Belgium, local authorities also favoured a central station over a peripheral one for the Brussels-Cologne HSR line (Moyano and Dobruszkes, 2017). Despite Belgian Railways initially considering a peripheral option, the municipality of Liège secured the station's location near the inner city. This decision underscored the city's preference for central locations that could better integrate with the existing urban fabric and stimulate local economic activities. Similar conflicts between national and local interests were observed in the cities of Linköping in Sweden (Hermelin and Gustafsson, 2022) and in Brno in Czech Republic (Kowalski, Marada, and Chmelík, 2023) which were both discussed extensively in the literature review of chapter 2.

These four cases illustrate the recurring theme of local opposition to peripheral HSR-stations and protectionism in the context of maintaining a central station as main node, driven by the desire to maximise local benefits. This trend is one of the key governance aspects that should be taken into account when considering peripheral HSR-stations.

4. Relocating HSR-services away from the city centre is in reality not as black and white.

The HSR-service relocation experiments in this thesis have a systematic methodology in which services are relocated from a central location (population density $> 1500 / \text{km}^2$) to a peripheral location (population density $< 300 / \text{km}^2$). An important metric in this procedure is that average speed is 130 km/h in every urban core. However, the reality is not that black and white. HSR-services are often relocated from central areas to less central / suburban areas, which can also provide a detour in which high speeds can be maintained longer. Examples of this are the discussed relocations of HSR-services from Amsterdam Centraal and Brno Main Station to, respectively, Amsterdam Zuid, and the new Brno station (Hermanides, 2018; Kowalski, Marada, and Chmelík, 2023).

The argument for suggesting peripheral detours in this thesis was provided in chapter 1, stating that infrastructure construction within cities costly and limited by spatial constraints. There are however also arguments to maintain them within the urban core, which include lower access/egress times, possibly better attachment with the PT network and possibly boosting the local economy. Therefore, relocating HSR-services from central to sub-urban areas, instead of peripheral areas, might also be worth to consider.

7.2.2. Discussion on highly-impactful assumptions

Throughout the three chapters that contain results, being chapter 4, chapter 5, and chapter 6, 46 assumptions have been described. The set of assumptions may be comprehensive, but it is not complete. All assumptions that were deemed potentially influential are included in the set.

The 46 assumptions have been ranked in two categories; the impact of the assumption and the likelihood of oversimplification. For discussion in this section, only assumptions that were labelled 'high' on impact and 'medium' or 'high' on likeliness of oversimplification were included. When the likeliness is high, it is known with certainty that the assumption oversimplifies reality, and thus that the assumption impacts the results in an unrealistic way. The assumptions that meet these conditions are provided in Table 7.4. The last column describes which sub-question results have been most affected by the assumption. The assumptions are discussed in this section in the order in which they impact the sub-questions, so first Q1, then Q2, Q3, et cetera. The one that is hypothesised to be the most impactful, A13, is discussed last.

It was concluded in the closure of chapter 5 that the conservative estimate of 350 seats per train (A26), based on Campos and de Rus (2009), might be too conservative. Laroche (2014) demonstrates this by mentioning that the initial TGV generation had 377 seats, whereas the typical French trains had a theoretical capacity of 450 seats as of 2014, and the newer Duplex double-decker trains can accommodate 512 seats. The impact of this assumption is that more bottlenecks have been defined for Q1

Table 7.4: Overview of highly-impactful assumptions for discussion.

ID	Assumption	Impact of assumption	Likelihood of oversimplification	Affects
A13	The average access/egress speed is 19 km/h for urban stations, while it is 27 km/h for peripheral stations.	High	High	Q2-Q5
A14	Train tickets for high-speed trains are equally expensive as those for conventional trains.	High	High	Q2-Q4
A15	Access/egress trips do not have travel costs, while the main long-distance modes do have travel costs.	High	High	Q1-Q4
A20	The total autonomous growth rate for long-distance travel in Europe between 2019 and 2050 is 13%.	High	Medium	Q1-Q4
A24	Long-distance trips are defined as trips from 200 km.	High	Medium	Q2-Q4
A26	The assumption of 350 seats per train is a conservative estimate based on historical data.	High	High	Q1
A32	A growth factor for commuter trains of 1.5% is assumed based on economic growth projections.	High	Medium	Q1
A35	Traffic demand is assumed to be uniform throughout the day, excluding rush hour effects.	High	High	Q1
A39	Induced demand effects of the new peripheral HSR-stations and corresponding infrastructure in Q3 and Q4 are not considered.	High	High	Q3-Q4
A46	The 'Both' experiment type assumes unlimited services, supplying every passenger with their preferred rail route.	High	High	Q2-Q4

than would have been the case if a higher seat capacity was selected.

In extension of A26, assumption A35 also concerns the saturation analysis of Q1. A35 assumes that demand is uniform throughout the day, excluding the effects of rush hours and their corresponding demands. This assumption affects the results of bottleneck identification, as stations will hit saturation points much faster during rush hours compared to the assumed full day span (7:00-23:00). In conclusion, where A26 suggested that too many bottlenecks might have been identified, A35 suggests that too few bottlenecks may have been identified.

The last assumption that affects the results of Q1 is A32, which assumes a growth factor for commuter trains of 1.5% based on EY (2023). The value fits the range of autonomous growth factors of Hilbers et al. (2020) and represents a scenario with relatively strong economic growth. Since this value was assumed in the context of the saturation analysis to find potential bottlenecks, it is not out-of-the-ordinary to assign a relatively high value, which will help in identifying potential bottlenecks. However, it is a discrepancy in comparison to the relatively low transport growth assumed for long-distance travel in chapter 4, being only 13% between 2024 and 2050 (A20). The approach of selecting a conservative percentage there, to not eventually overestimate passenger welfare effects, also makes sense, but it does not align with the assumed 1.5% here. This is an inconsistency that provides a distorted ratio of the contribution of commuter and long-distance trains in Figure 7.1. It was detailed in section 7.1 of this chapter that 38% of the saturation of the bottlenecks arises from long-distance travel. Given that long-distance travel has been assigned with a relatively low growth factor (A20), and commuter trains with a high growth factor (A32), it is suggested that this value would in reality probably be closer to 50%. In extension of this discussion, the conservative estimate of A20 is also expected to lead to relatively low passenger welfare effects in the experiments of Q2, Q3, and Q4.

The next assumption (A14) that affects the passenger welfare results of Q2-Q4 is A14. A14 assumes that the tickets for the HSR train are equally expensive as those for conventional trains. Literature, however, explicitly states that 'fares and track access charges for high speed services are typically greater than those for conventional rail' (European Commission, 2016). It is expected that the travel costs that are applied in this research, which were applied from Tanner (2023), concern mostly HSR. This implies that the costs for travel on conventional railway edges have been modelled at a too high value, leading to an underestimation of passenger flows on the conventional railways and an overestimation of passenger flows on the high-speed railways. This assumption therefore leads to an overestimation

of the passenger welfare effects in Q2-Q4, since they explicitly concern HSR-stations.

Another impactful assumption is that access/egress trips are essentially free (A15). The transport model does not assign an estimate of ticket prices to the access and egress trips, but does assign costs to the in-vehicle time per distance unit. This makes the access/egress segment relatively too attractive in comparison to the in-vehicle segment of the main mode. This is assumed to be impactful, since excluding access/egress travel costs will overestimate the use of peripheral stations, i.e. stations at a relatively large distance, by OD-passengers. This statement holds under the precondition that the β_{TC} acts in a similar way for the in-vehicle segment as for the access and egress segments. In addition, including access/egress costs would result in both plane and train modes performing worse in the modal split, whereas car trips, which do not involve an access/egress element, would perform better.

A24 concerns the impacts of the exclusion of long-distance trips below 200 km. This assumption is divergent from the literature, where 100 km is often selected according to Tanner (2023). This scope of assuming that long-distance travel is at least 200 km arises from the passenger distribution set that was adapted from Grolle et al. (2024), which generated the dataset on air passenger data for travels of at least 200 km. This assumption is expected to overestimate the passenger welfare effects in this study. This statement arises from the fact that the welfare benefits are generated solely by traversing passengers when the peripheral station is assumed to be less accessible than the urban station. Passengers that would travel only 100 kilometres in this model would not likely traverse stations and, therefore, yield negative welfare effects of HSR-service relocation to the outskirts. In addition, such 'short' long-distance trips could in reality also be used by commuting traffic, in which case relocation to the city outskirts is expected to lead to substantial negative passenger welfare effects. An example of this is the HSR railway between Brno and Prague, which is 180 km (Google Inc., 2024), where Brno citizens were strongly opposed to the relocation of the HSR-station away from the centre for commuting reasons. In conclusion, assuming that long-distance trips only occur from 200 kilometres in the model, means that the passenger welfare benefits are expected to be overestimated.

Assumption A39 inherently suggests that the passenger welfare effects are underestimated. This study has considered the induced demand effects anticipated with the implementation of the Comprehensive TEN-T, which involves the construction of new railways in Europe. However, it has not taken into account the additional induced demand effects resulting from the creation of a new station and the corresponding infrastructure in Q3 and Q4. If these additional benefits were included, it would have been essential to apply the rule-of-half to the user benefits of this group of switchers. Quantitatively, this would mean that some years after the construction of the peripheral detour, the demand would have increased by 25% from the modelled situation for 2050. Applying the rule-of-half would suggest that the passenger welfare results could be approximately 12.5% higher than currently estimated.

The impacts of A46 have been described previously in this chapter. The application of the 'Both' scenario, where passengers can take their preferred route in an unconstrained manner, assumes unlimited services. This perspective is overly optimistic, suggesting that the 'Both' scenario overestimates passenger welfare effects. Consequently, the results of the 'Both' experiments should not be seen as the probable passenger welfare effects, but rather as an indication of the near-maximum potential welfare effects. Why it is near-maximum is described in section 6.2.

The last and most impactful assumption on the results is the course approach of assuming that the average access/egress speed is 19 km/h for urban stations, while it is 27 km/h for peripheral stations (A15). In general, one would expect peripheral stations to have an access/egress time that is higher than that of their urban counterpart. However, as previously stated, this study is black and white in its definition of urban and central stations, leading to an overestimation of the attractiveness of peripheral stations that are located relatively close to the urban centre. An example of this is the peripheral HSR-station of Copenhagen Astrup Airport (access/egress time of 0.83 hour), which is more attractive than its central counterpart of Copenhagen Hovedbanegård (access/egress time of 0.89 hour). This is caused by the fact that Astrup station is located just outside the urban centre border (OECD, 2023), but has a population density of <300. Therefore, it was identified as a peripheral station (United Nations Statistical Commission, 2020), and assigned with an access/egress speed of 27 km/h. Examples of

such peripheral stations with overestimated accessibility form the minority of experiments, but are frequent. For comprehensiveness; these experiments include, next to Copenhagen Astrup, Montpellier Sud-de-France, Paris Charles de Gaulle TGV and Frankfurt Am Main Flughafen Fernbahnhof for Q2, Amsterdam Schiphol and Cologne-Bonn Airport for Q3, and Cologne W, Florence N, Mannheim E and Frankfurt S of the best performing results of Q4.

The consequence of this assumption is that passenger welfare effects for these stations are overestimated, as a result of OD-passengers that prefer the peripheral station over the urban station. This overestimation effect is present in the 'Both' scenario and the 'Peripheral Only' scenario, but especially excessive in the last one where it assigns all passengers to the peripheral station. The phenomenon that the 'PO' scenario unexpectedly outperforms the 'Both' scenario, is seen in both Table 7.1 and Table 7.2. This description makes it sound as if A15 has led to a doubling of passenger welfare effects, but it is generally much less. This arises from the fact that the ratio of traversing passengers / OD-passengers is on average 3.9 in the bottleneck set, which concerns all urban nodes that lead to overestimation of peripheral station accessibility in the experiments. On average, only about 20% of the passengers in these cities concern OD-passengers, which makes that the overestimation of A15 has relatively limited impact in comparison to the passenger welfare benefits that are experienced by the traversing passengers. The exception to this is experiment Q3.1, where HSR-services are relocated to Amsterdam Schiphol. Here, only 1/3 of passengers are traversing passengers, which do not experience welfare benefits due to the relocation since it does not provide a detour, while the 2/3s of OD-passengers experience welfare benefits due to the fact that the model assigns a too beneficial access/egress speed, and therefore access/egress time. NB: These statements are all made under the assumption that in reality peripheral stations would generally have a higher access/egress time than their urban counterparts.

From A15 one can conclude that passenger welfare effects for OD-passengers are frequently estimated to be too beneficial in the experiments. However, A39, on the effects of induced demand, and A20, on the conservative growth factor, suggest that the passenger welfare effects are underestimated. When making up the balance between all the assumptions that influence the passenger welfare effect results, three of these highly impactful assumptions suggest that the passenger welfare effects are underestimated (A13; A20; A39), while the other four suggest that they are overestimated (A14; A15; A24; A46). No conclusive judgement can be made on the matter of overestimation of underestimation of the passenger welfare results, since the effects of these assumptions were not quantified, but it is expected that the passenger welfare effects due to relocation of HSR-services from city centres to outskirts are rather overestimated than underestimated.

7.3. Recommendations

7.3.1. Policy recommendations

The section discusses suggestions that can be provided based upon the results and conclusions of this research. It starts off with recommendations to international policy-makers, and then shifts to considerations for local policy-makers.

This study has shown that HSR can become a more attractive mode through specific relocations of HSR-services, increasing the utility through peripheral detours. Since the EU aims for railway transport to play an essential role in achieving the decarbonisation targets of the Green Deal (Keersmaecker and Wartberger, 2021), all possible policy measures should be considered to help achieve this goal. It is therefore recommended to consider the possibility of peripheral HSR-detours and corresponding stations, which could also provide a solution to capacity issues at stations. Peripheral stations are especially worth considering when data from railway operators show that there are many traversing passengers that would benefit from it, which is expected along main corridors and not at the ends of the network, and when the peripheral detour provides a route that is shorter and faster than the urban route. Especially when a network with a peripheral HSR-station can be designed as in the upper half of Figure 7.3, peripheral stations should be considered. In line with the discussed statements that HSR-projects generally struggle with financial feasibility, the EU could fund such infrastructure if models illustrate that substantial passenger welfare benefits can be generated that effectuate a positive social

benefit-cost ratio. Lastly, this study does not consider externalities, but it is expected that they are lower for the new HSR infrastructure on the city outskirts than they are for the expansion of HSR within the city (Widmer and Hidber, 2000). Therefore, it is crucial that they are included in the decision-making process on HSR-station allocation. The recommendations in this paragraph apply to some extent also to national governments, although they will not experience the same scale of passenger welfare benefits within their borders as the EU will on an international scale.

The recommendation to local policy-makers is not to dismiss a peripheral station at first hand. Although HSR-stations can lead to job creation and local economic activities in the area of their allocation (Moyano and Dobruszkes, 2017), which is why many municipalities prefer them located centrally, it is recommended to also weigh the potential benefits of peripheral allocation. This concerns not only benefits for international traversing passengers, but also local benefits. Allocating HSR-services peripherally can for example relieve pressure from crowded public spaces in the city centre, create capacity for more commuter services to the central stations, lead to less externalities and be financially more feasible. These last two arguments are especially true when comparing the possibility of constructing a peripheral detour with an urban railway tunnel. An example which is provided by European Court of Auditors (2018b). This report describes how the new railway tunnel in Stuttgart exceeds the planned costs with more than a billion euro. A peripheral detour would have been not only more cost-effective and less burdensome in terms of noise and CO₂ emissions, but could also have led to substantial passenger welfare benefits. As has been provided in the Q4 experiment of Stuttgart W.

Although benefits of peripheral stations to municipalities have been described, the access/egress distances for accessing HSR-services would increase nevertheless. The impact of this depends on the number of HSR-services that remain allocated at a central station, if any, and how many are relocated to a peripheral station. In both scenarios, it is advisable to establish robust public transportation links between the city center and the outlying station. For example, peripheral airports are frequently connected by public transit, such as in Bergen (Google Inc., 2024). A notable example of effective public transport in the context of HSR relocation is the metro line between Amsterdam Centraal and the proposed new HSR station at Amsterdam Zuid.

Lastly, the literature describes how government levels should converge in the decision-making on HSR (Marti-Henneberg, 2015). This study supports this statement, since benefits of peripheral stations often occur on a large scale, while the disadvantages are often experienced on a local scale. To accurately weigh the different interests, this thesis would suggest to include not only government levels, as supposed in Marti-Henneberg (2015), but also to include operators and infrastructure managers in the decision-making process. This would ensure that potential peripheral HSR-stations are not only located efficiently, but also operated efficiently. This is a crucial aspect as efficient operations cannot be taken for granted in peripheral stations (Moyano and Dobruszkes, 2017), as described in the literature review of chapter 2.

7.3.2. Research recommendations

This research fills the knowledge gaps defined in chapter 1, but identified some new ones along the way. These are included in the list below, together with some general suggestions for research.

1. This study presents strategic network configurations for peripheral HSR-stations, assuming that the aim is maximum passenger welfare. Borgogno (2023) on the other hand developed a strategic network growth model that concerns infrastructure allocation between cities, while assuming that stations remain to exist in the same locations. The research by Roy and Maji (2022) provides a model that assigns the most strategic station locations along existing railway lines. A combination of these three models, that aims for a combined strategic allocation of edges and nodes would be novel in the context of high-speed rail. However, it is expected that such a research would be computationally very heavy, since neither edges nor nodes would be bound to existing locations.
2. This study assumes economically rational behaviour from its modelled passengers, assuming that they only care about time and money. While in reality, long-distance rail travellers might have a very strong liking for beginning and terminating their long-distance journey inside a city. As described in the introduction of this thesis, exiting the train in the midst of a city is often viewed as

one of the main selling points of HSR-trips (Lonely Planet, 2022). It could therefore be interesting to perform a stated preference survey on this subject to estimate how rail passengers actually value such attributes.

3. It is hypothesised that having multiple peripheral HSR-stations in sequence, distributed over different urban nodes, would amplify their separate welfare results. Research on this topic could prove very valuable, with China being the perfect case study since peripheral HSR-stations are conventional there. In the European context, it could be performed by running an altered experiment of this study's model with multiple peripheral stations in sequence as input.
4. It would have been valuable for interpretation of the results if the total consumer surplus (CS) per experiment would have been split up into a CS of traversing passengers and a CS of OD-passengers, and this is recommended to any student or scientist that aims to do similar research. These results would have been achievable, if they would have been stored per experiment. Say that you want to split the total consumer surplus for Madrid into the described categories, then you could sum all of the CS values for all OD-pairs that contain Madrid as either origin or destination, which would provide the CS for OD-passengers. The CS for traversing passengers could then be found by subtracting the CS for OD-passengers from the total CS. Having this division of passenger welfare effects would assist in interpretation of their origins.
5. This research has improved the approach of quantifying access/egress distances, in comparison to similar studies, by using the population-density based approach. Comparison to the greater circle distance approach of Grolle et al. (2024), which is easier to apply, illustrated that this new approach improves the realism of the research. In some cases the population weighted density approach per catchment area provided access/egress distances that varied a factor two with the greater circle distance approach. It would therefore be advisable to incorporate this approach in future research, if time allows for the extra effort.
6. Long-distance travel by rail is a study field in which the acquisition of data is a struggle, as has previously been defined by Donners (2016). It is therefore recommended to future researchers on the topic to first sort out all available data that could assist in filling a knowledge gap before committing to a research. The data sources that turned out to be most useful were (Eurostat, 2024) and (4TU Federation, 2024), with the latter containing data from e.g. Tanner (2023) and Grolle et al. (2024). The data of this research is also published at 4TU Federation (2024) around the time of publication, specifically including the geographical data of the European railway network as envisioned for 2050 in the TEN-T (European Commission, 2021b).
7. In addition to scarcity of data, models are also often not openly available. That is why the transport model of this thesis is also uploaded to 4TU Federation (2024). It allows both for testing future adaptations of the network, as well as for policy changes. Such policies could include sensitivity analyses of different carbon cost internalisation measures like the ETS and TMC (Tanner, 2023).
8. It is expected that the externalities of peripheral HSR-stations, both during construction and operation, are lower than those of centrally-located stations. An example of this was provided in the SCBA study concerning the Paris Charles de Gaulle HSR-station (Widmer and Hidber, 2000). Researching how large these externality benefits are would provide the next piece to the puzzle for execution of reliable SCBAs on peripheral HSR-stations.
9. Lastly, Adler, Pels, and Nash (2010) describe in their research that aggregate network effects should be taken into account when evaluating rail infrastructure in cost-benefit analyses, since they found these to be substantial. This study has illustrated the same. The reason that experiment Lille S (Q4) generates the highest possible result of Q4 is not due to a distinct railway connection with a nearby town like Gent, but due to the fact that all nodes on the mainland of Europe are connected with the UK via Lille. This essential location, with high betweenness centrality, in the network is what contributes to the high passenger welfare effects. It is therefore strongly recommended to take large networks into account when performing SCBAs for HSR-infrastructure, ensuring that the aggregate network effects are correctly taken into account.

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A

TEN-T passenger rail network

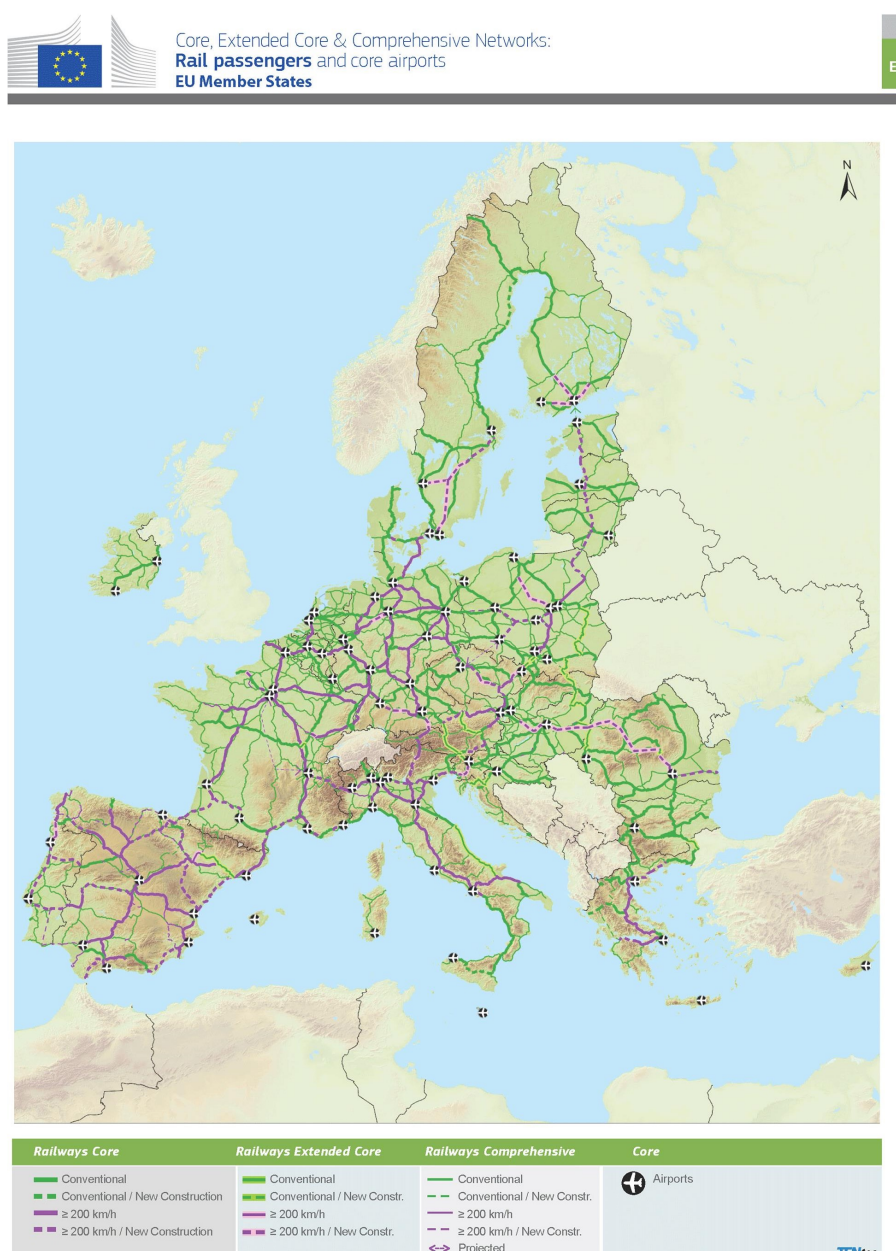


Figure A.1: The latest version of the TEN-T passenger rail network (European Commission, 2021b).

B

Station Selection Results

This appendix presents in three tables the stations that were selected according to the selection procedure described in section 4.2. The entries are ordered alphabetically according to the country codes (CC) of the stations. The selection is presented in Table B.1, Table B.2 and Table B.3.

The tables contain, next to the country code, the urban area name and the station name, also characteristics of the stations. These characteristics include whether the stations are terminus stations (Term), whether they serve high-speed trains (HSR), and the centrality typology (Typology), based on the population density at its location. The first two characteristics are presented by binaries. This means that a station is a terminus station that serves HSR if both are 1, and that it is a through station that does not serve HSR if both are 0.

Table B.1: Selection of European Railway Stations (1/3)

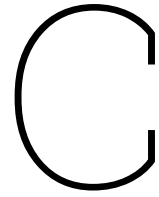
CC	Area	Station name	Term	HSR	Centrality	Selection
AL	Tirana	Tirana Station	1	0	Central	I
AT	Linz	Linz Hbf	0	1	Central	I
AT	Vienna	Wien Hauptbahnhof	0	1	Central	I
AT	Vienna	Flughafen Wien	0	1	Peripheral	VI
BA	Sarajevo	Sarajevo Station	1	0	Central	I
BE	Antwerpen	Antwerpen Centraal	0	1	Central	I
BE	Gent	Gent Sint-Pieters	0	0	Central	V
BE	Brussels	Station Brussel-Centraal	0	1	Central	I
BE	Liege	Liege Guillemins	0	1	Central	V
BE	Brussels	Station Brussels Airport-Zaventem	0	1	Peripheral	VI
BG	Plovdiv	Plovdiv Central Railway Station	0	0	Central	I
BG	Sofia	Sofia Central Station	0	0	Urban	I
BY	Minsk	Minsk (Pasazyrski) Station	0	0	Central	I
CH	Zurich	Zurich Hbf	1	0	Central	I
CH	Geneva	Geneva Station	0	0	Central	I
CH	Basel	Basel SBB Station	0	0	Central	V
CZ	Ostrava	Ostrava Main Station	0	1	Central	I
CZ	Brno	Brno Main Station	0	1	Urban	E
CZ	Prague	Prague Hbf	0	1	Central	I
DE	Dusseldorf	Dusseldorf Hauptbahnhof	0	1	Central	I
DE	Cologne	Koln Hbf	0	1	Central	I
DE	Aachen	Aachen Hbf	0	1	Central	I
DE	Ruhrgebiet (Essen)	Essen Hbf	0	1	Central	I
DE	Bremen	Bremen Hbf	0	1	Central	I
DE	Hamburg	Hamburg Hbf	0	1	Central	I
DE	Hannover	Hannover Hbf	0	1	Central	I
DE	Leipzig	Hauptbahnhof Leipzig	1	1	Central	I
DE	Frankfurt Am Main	Frankfurt am Main Hauptbahnhof	1	1	Central	I
DE	Saarbrücken	Saarbrücken Hbf	0	1	Central	I
DE	Karlsruhe	Karlsruhe Hbf	0	1	Central	I
DE	Mannheim	Mannheim Hbf	0	1	Central	I
DE	Kiel	Kiel Hbf	1	0	Central	I
DE	Berlin	Berlin Hbf	0	1	Central	I
DE	Dresden	Dresden Hbf	0	1	Central	I
DE	Stuttgart	Stuttgart Hbf	1	1	Central	I
DE	Munich	München Ost	0	1	Central	III
DE	Frankfurt Am Main	Frankfurt Flughafen Fernbahnhof	0	1	Peripheral	VI
DE	Dusseldorf	Bahnhof Düsseldorf Flughafen	0	1	Peripheral	VI
DE	Leipzig	Bahnhof Leipzig/Halle Flughafen	0	1	Peripheral	VI
DE	Munich	München Hbf	1	1	Central	I
DK	Copenhagen	Københavns Hovedbanegård	0	1	Central	I
DK	Århus	Århus Hovedbanegård	1	0	Central	I
DK	Copenhagen	Københavns Lufthavn Kastrup	0	1	Peripheral	VI
EE	Tallinn	Tallinn Station	1	1	Central	II
EL	Thessaloniki	Thessaloniki Station	1	1	Central	I
EL	Athens	Athens Station	1	1	Central	I
ES	Sevilla	Sevilla-Santa Justa	0	1	Central	V
ES	Valencia	Valencia-Joaquín Sorolla	1	1	Central	II

Table B.2: Selection of European Railway Stations (2/3)

CC	Area	Station name	Term	HSR	Centrality	Selection
ES	Zaragoza	Zaragoza Delicias	0	1	Central	V
ES	Barcelona	Barcelona-Sants	0	1	Central	II
ES	Bilbao	Bilbao Abando	1	1	Central	II
ES	Madrid	Madrid Chamartín	0	1	Central	IV
ES	Madrid	Madrid Atocha	0	1	Central	IV
ES	Madrid	Madrid Barajas Airport	1	1	Peripheral	VI
FI	Helsinki	Helsinki Central Station	0	1	Central	I
FI	Tampere	Tampere Station	0	0	Central	I
FI	Helsinki	Helsinki Airport	0	1	Peripheral	VI
FR	Rouen	Gare Rouen Rive Droite	1	1	Central	V
FR	Lille	Gare Lille-Flandres	1	1	Central	II
FR	Paris	Gare La Défense	1	1	Central	IV
FR	Paris	Gare du Nord	1	1	Central	IV
FR	Paris	Gare du Est	1	1	Central	IV
FR	Paris	Gare du Lyon	1	1	Central	IV
FR	Paris	Gare Austerlitz	1	1	Central	IV
FR	Paris	Gare Montparnasse	1	1	Central	IV
FR	Strasbourg	Gare de Strasbourg	0	1	Central	I
FR	Rennes	Gare de Rennes	0	1	Central	I
FR	Nantes	Gare de Nantes	0	0	Central	I
FR	Bordeaux	Bordeaux Saint-Jean	0	1	Central	V
FR	Toulouse	Gare Toulouse Matabiau	0	1	Central	V
FR	Grenoble	Gare de Grenoble	0	0	Central	I
FR	Marseille	Marseille Saint-Charles	1	1	Central	II
FR	Lyon	Part Dieu	0	1	Central	V
FR	Nice	Nice-Ville	0	1	Central	V
FR	Toulon	Gare de Toulon	0	1	Central	I
FR	Montpellier	Montpellier-Saint-Roch	0	1	Central	V
FR	Montpellier	Montpellier-Sud-de-France	0	1	Peripheral	VI
FR	Lille	Gare Lille-Europe	0	1	Central	III
FR	Lyon	Lyon-Saint-Exupéry	0	1	Peripheral	VI
FR	Paris	Aéroport Charles de Gaulle 2 TGV station	0	1	Peripheral	VI
FR	Paris	Paris Marne-La-Vallee-Chessy TGV	0	1	Peripheral	VI
HR	Zagreb	Zagreb Main Station	0	0	Central	I
HU	Budapest	Budapest Keleti	1	1	Central	IV
HU	Budapest	Budapest Nyugati	1	1	Central	IV
HU	Budapest	Budapest Déli	1	1	Central	IV
IT	Venice	Venezia Santa Lucia	1	1	Central	II
IT	Verona	Verona Porta Nuova	0	1	Central	V
IT	Brescia	Brescia Stazione	0	0	Central	I
IT	Milano	Milano Centrale	1	1	Central	I
IT	Turin	Torino Porto Nuova	1	1	Central	I
IT	Genoa	Genova Piazza Principale	0	1	Central	I
IT	Bologna	Bologna Centrale	0	1	Central	I
IT	Florence	Firenze Santa Maria Novella	1	1	Central	II
IT	Palermo	Palermo Centrale	0	0	Central	I
IT	Catania	Catania Centrale	0	0	Urban	I
IT	Bari	Bari Centrale	0	1	Central	I
IT	Napoli	Napoli Centrale	0	1	Central	I
IT	Rome	Roma Termini	1	1	Central	II

Table B.3: Selection of European Railway Stations (3/3)

CC	Area	Station name	Term	HSR	Centrality	Selection
IT	Rome	Rome Tiburtina	0	1	Central	III
IT	Turin	Torino Porta Susa	0	1	Central	III
LT	Vilnius	Vilnius Station	0	1	Central	I
LU	Luxembourg	Luxembourg Station	0	0	Central	I
LV	Riga	Riga Central Station	0	1	Central	I
LV	Riga	Riga International Airport	0	1	Peripheral	VII
MD	Chisinau	Chisinau Station	0	0	Urban	I
ME	Podgorica	Podgorica Station	0	0	Central	I
MK	Skopje	Skopje Transportation Centre	0	0	Central	I
NL	Amsterdam	Amsterdam Zuid	0	1	Central	E
NL	Rotterdam	Rotterdam Centraal	0	1	Central	I
NL	Utrecht	Utrecht Centraal	0	0	Central	I
NL	Eindhoven	Eindhoven Centraal	0	0	Central	I
NL	Groningen	Groningen Station	1	0	Central	I
NL	Amsterdam	Schiphol Airport	0	1	Peripheral	VI
NO	Bergen	Bergen Stasjon	1	0	Central	I
NO	Oslo	Oslo Sentralstasjon	0	1	Central	I
NO	Oslo	Oslo airport station	0	1	Peripheral	VI
PL	Gdansk	Gdansk Main Station	0	0	Central	I
PL	Lublin	Lublin Main Station	0	0	Central	I
PL	Warsaw	Warsaw Central Station	0	1	Central	I
PL	Lodz	Lodz Fabryczna	0	1	Central	V
PL	Poznan	Poznan Main Station	0	1	Central	I
PL	Wroclaw	Wroclaw Main Station	0	1	Central	I
PL	Katowice	Katowice Station	0	1	Central	I
PL	Krakow	Krakow Main Station	0	0	Central	I
PL	Rzeszow	Rzeszow Main Station	0	0	Central	I
PT	Lisbon	Lisboa Oriente	0	1	Urban	V
PT	Porto	Porto Campanha	0	1	Central	V
RO	Iasi	Iasi Railway Station	0	0	Central	I
RO	Cluj-Napoca	Cluj-Napoca Station	0	1	Central	I
RO	Bucharest	Gara Bucuresti Nord	1	1	Central	II
RS	Belgrade	Belgrade Central Station	0	0	Central	I
RU	Kaliningrad	Kalinigrad Station	0	0	Central	I
RU	Moscow	Leningradsky Station	1	0	Central	V
RU	St. Petersburg	St. Petersburg-Station	0	0	Central	I
SE	Göteborg	Goteborgs Central	0	1	Central	I
SE	Stockholm	Stockholm Central	0	1	Central	I
SI	Ljubljana	Ljubljana Station	0	1	Central	I
SK	Kosice	Kosice Station	0	0	Central	I
SK	Bratislava	Bratislava Main Station	0	0	Central	I
TR	Ankara	Ankara Station	0	1	Central	I
TR	Istanbul	Istanbul Sirkeci Station	0	1	Central	V
UA	Kiev	Kiev Pasazhyrskyi Station	0	0	Central	I
UK	London	Euston Station	1	1	Central	IV
UK	London	St Pancras International	1	1	Central	IV
UK	London	King's Cross	1	1	Central	IV
UK	Birmingham	Birmingham Interchange	0	1	Peripheral	E
UK	Birmingham	Birmingham Curzon Street	1	1	Central	E
UK	Liverpool	Liverpool Lime Street	1	1	Central	II
UK	Manchester	Manchester Picadilly Circus	0	1	Central	V
UK	Leeds	Leeds Station	0	0	Central	I
UK	Newcastle Upon Tyne	Newcastle Station	0	1	Central	I
UK	Edinburgh	Edinburgh Waverley	0	1	Central	V
UK	Glasgow	Glasgow Central	1	1	Central	I
XK	Pristina	Pristina Station	0	0	Urban	I



Saturation Analysis Results

C.1. Commuter train traffic results

The datasets below include station names and their whereabouts, the estimated commuter train traffic demand in 2050, the train traffic per station as according to the source, the year in which the data was recorded, and the source itself. Some names are abbreviated for editorial reasons. These include:

- Hbf as an abbreviation for Hauptbahnhof;
- Kobenhavns Hovedbanegård is abbreviated to København H;
- Frankfurt Am Main to Frankfurt;
- Ruhrgebiet (Essen) to Ruhrgebiet;
- Newcastle Upon Tyne to Newcastle;
- Valencia-Joaquín Sorolla to Valencia-Joaquín.

These abbreviations are also applied in the next section of this appendix.

Table C.1: Commuter train traffic estimation per station (table 1/2).

AREA	NAME	Com_Demand 2050	Data	Year	Source
Rouen	Gare Rouen Rive Droit	75145	49584	2015	Eurostat (2024)
Lille	Gare Lille-Flandres	289211	182500	2012	Heddebaut (2018)
Paris	Gare La Défense	81776	58130	2020	Eurostat (2024)
Paris	Gare du Nord	1031188	766500	2023	RTL (2017)
Paris	Gare du Est	222744	158337	2020	Eurostat (2024)
Paris	Gare du Lyon	536926	365000	2017	UIC (n.d.)
Paris	Gare Austerlitz	49426	35134	2020	Eurostat (2024)
Paris	Gare Montparnasse	62637	44525	2020	Eurostat (2024)
Strasbourg	Gare de Strasbourg	119426	78803	2015	Eurostat (2024)
Rennes	Gare de Rennes	73449	48465	2015	Eurostat (2024)
Bordeaux	Bordeaux Saint-Jean	86880	57328	2015	Eurostat (2024)
Toulouse	Toulouse Matabiau	75574	49868	2015	Eurostat (2024)
Marseille	Marseille Saint-Charles	154042	109500	2020	Marseille Tourisme (2024)
Lyon	Part Dieu	395253	298205	2024	Trainline (2024)
Nice	Nice-Ville	70403	46455	2015	Eurostat (2024)
Toulon	Gare de Toulon	50683	33443	2015	Eurostat (2024)
Montpellier	Montpellier-Saint-Roch	56555	37318	2015	Eurostat (2024)
Budapest	Budapest Keleti	148876	105828	2020	Eurostat (2024)
Linz	Linz Hbf	125343	89100	2020	Eurostat (2024)
Vienna	Wien Hbf	123599	87860	2020	Eurostat (2024)
Antwerpen	Antwerpen Centraal	63135	41660	2015	Eurostat (2024)
Brussels	Brussel-Centraal	107570	70980	2015	Eurostat (2024)
Liege	Liege Guillemins	119601	78919	2015	Eurostat (2024)
Ostrava	Ostrava Main Station	24755	17596.5	2020	Eurostat (2024)
Prague	Prague Hbf	344945	245203	2020	Eurostat (2024)
Dusseldorf	Dusseldorf Hbf	555136	394617	2020	Eurostat (2024)
Cologne	Koln Hbf	481218	342072	2020	Eurostat (2024)
Aachen	Aachen Hbf	110022	78209	2020	Eurostat (2024)
Ruhrgebiet	Essen Hbf	330360	234835	2020	Eurostat (2024)
Bremen	Bremen Hbf	205495	146076	2020	Eurostat (2024)
Hamburg	Hamburg Hbf	256905	182620	2020	Eurostat (2024)
Hannover	Hannover Hbf	339424	241279	2020	Eurostat (2024)
Leipzig	Hbf Leipzig	288968	205412	2020	Eurostat (2024)
Frankfurt	Frankfurt Hbf	842722	599047	2020	Eurostat (2024)
Saarbrücken	Saarbrücken Hbf	133651	95006	2020	Eurostat (2024)
Karlsruhe	Karlsruhe Hbf	463197	329262	2020	Eurostat (2024)
Mannheim	Mannheim Hbf	325693	231518	2020	Eurostat (2024)
Berlin	Berlin Hbf	505307	328500	2014	Trains (n.d.)
Dresden	Dresden Hbf	207155	147255	2020	Eurostat (2024)
Stuttgart	Stuttgart Hbf	355383	252623	2020	Eurostat (2024)
Munich	München Ost	385688	274166	2020	Eurostat (2024)
Copenhagen	København H	298328	212065	2020	Eurostat (2024)
Tallinn	Talinn Station	15023	10679	2020	Eurostat (2024)
Thessaloniki	Thessaloniki Station	8025	5704	2020	Eurostat (2024)
Athens	Athens Station	43360	30822	2020	Eurostat (2024)
Sevilla	Sevilla-Santa Justa	80502	57224	2020	Eurostat (2024)
Valencia	Valencia-Joaquín	10063	7153	2020	Eurostat (2024)
Zaragoza	Zaragoza Delicias	47644	33868	2020	Eurostat (2024)
Barcelona	Barcelona-Sants	372973	265127	2020	Eurostat (2024)
Bilbao	Bilbao Abando	70184	49890	2020	Eurostat (2024)
Madrid	Madrid Chamartín	342562	243509	2020	Eurostat (2024)

Table C.2: Commuter train traffic estimation per station (table 2/2).

AREA	NAME	Com_Demand 2050	Data	Year	Source
Madrid	Madrid Atocha	513373	364930	2020	Eurostat (2024)
Helsinki	Helsinki Central Station	266676	189566	2020	Eurostat (2024)
Porto	Porto Campanha	246245	175042	2020	Eurostat (2024)
Cluj-Napoca	Cluj-Napoca Station	51860	36864	2020	Eurostat (2024)
Bucharest	Gara Bucuresti Nord	49883	35459	2020	Eurostat (2024)
Gothenburg	Goteborgs Central	133196	94682	2020	Eurostat (2024)
Stockholm	Stockholm Central	235647	167509	2020	Eurostat (2024)
Ljubljana	Ljubljana Station	44005	31281	2020	Eurostat (2024)
Ankara	Ankara Station	51438	36564	2020	Eurostat (2024)
London	Euston Station	140776	92891	2015	Eurostat (2024)
London	St Pancras International	40354	26628	2015	Eurostat (2024)
London	King's Cross	143997	95017	2015	Eurostat (2024)
Birmingham	Birmingham Curzon Street	0	0	0	Eurostat (2024)
Liverpool	Liverpool Lime Street	124461	82126	2015	Eurostat (2024)
Manchester	Manchester Picadilly Circus	364867	240758	2015	Eurostat (2024)
Newcastle	Newcastle Station	125924	83091	2015	Eurostat (2024)
Edinburgh	Edinburgh Waverley	228882	151028	2015	Eurostat (2024)
Glasgow	Glasgow Central	109269	72101	2015	Eurostat (2024)
Oslo	Oslo Sentralstasjon	367052	242200	2015	Eurostat (2024)
Venice	Venezia Santa Lucia	93557	66504	2020	Eurostat (2024)
Verona	Verona Porta Nuova	71625	50914	2020	Eurostat (2024)
Milano	Milano Centrale	129798	92267	2020	Eurostat (2024)
Turin	Torino Porto Nuova	61893	43997	2020	Eurostat (2024)
Genoa	Genova Piazza Principale	97822	69537	2020	Eurostat (2024)
Bologna	Bologna Centrale	141998	100939	2020	Eurostat (2024)
Florence	Firenze Santa Maria Novella	133256	94724	2020	Eurostat (2024)
Bari	Bari Centrale	51735	36776	2020	Eurostat (2024)
Napoli	Napoli Centrale	85139	60521	2020	Eurostat (2024)
Vilnius	Vilnius Station	39275	25915	2015	Eurostat (2024)
Riga	Riga Central Station	140960	100201	2020	Eurostat (2024)
Amsterdam	Amsterdam Zuid	200465	142500	2020	Eurostat (2024)
Rotterdam	Rotterdam Centraal	220266	156575	2020	Eurostat (2024)
Warsaw	Warsaw Central Station	173509	119720	2018	Eurostat (2024)
Lodz	Lodz Fabryczna	65595	45260	2018	UTK (2019)
Poznan	Poznan Main Station	199431	137605	2018	UTK (2019)
Wroclaw	Wroclaw Main Station	212126	146365	2018	UTK (2019)
Katowice	Katowice Station	189909	131035	2018	UTK (2019)
Istanbul	Istanbul Sirkeci Station	127946	90950	2020	Eurostat (2024)
Munich	Munchen Hbf	341041	242428	2020	Eurostat (2024)
Turin	Torino Porta Susa	126488	89913	2020	Eurostat (2024)
Rome	Roma Termini	177027	125839	2020	Eurostat (2024)
Rome	Rome Tiburtina	148638	105659	2020	Eurostat (2024)
Budapest	Budapest Nyugati	36893	26226	2020	Eurostat (2024)
Budapest	Budapest Déli	68025	48356	2020	Eurostat (2024)
Lille	Gare Lille-Europe	92989	61359	2015	Eurostat (2024)

C.2. Station capacity results

Table C.3: Railway stations capacity data (table 1/2).
Retrieved by manual inspection of OpenRailwayMap ((Matheisen et al., 2024).

AREA	NAME	Cap_Station (2050)	Tracks	Terminus
Rouen	Gare Rouen Rive Droit	186880	8	1
Lille	Gare Lille-Flandres	397120	17	1
Paris	Gare La Défense	186880	8	1
Paris	Gare du Nord	747520	32	1
Paris	Gare du Est	677440	29	1
Paris	Gare du Lyon	513920	22	1
Paris	Gare Austerlitz	490560	21	1
Paris	Gare Montparnasse	654080	28	1
Strasbourg	Gare de Strasbourg	981120	14	0
Rennes	Gare de Rennes	700800	10	0
Bordeaux	Bordeaux Saint-Jean	981120	14	0
Toulouse	Gare Toulouse Matabiau	840960	12	0
Marseille	Marseille Saint-Charles	327040	14	1
Lyon	Part Dieu (central)	770880	11	0
Nice	Nice-Ville	490560	7	0
Toulon	Gare de Toulon	350400	5	0
Montpellier	Montpellier-Saint-Roch	420480	6	0
Budapest	Budapest Keleti	280320	12	1
Linz	Linz Hbf	840960	12	0
Vienna	Wien Hauptbahnhof	840960	12	0
Antwerpen	Antwerpen Centraal	981120	14	0
Brussels	Station Brussel-Centraal	420480	6	0
Liege	Liege Guillemins	630720	9	0
Ostrava	Ostrava Main Station	560640	8	0
Prague	Prague Hbf	560640	8	0
Dusseldorf	Dusseldorf Hauptbahnhof	1121280	16	0
Cologne	Koln Hbf	770880	11	0
Aachen	Aachen Hbf	490560	7	0
Ruhrgebiet (Essen)	Essen Hbf	840960	12	0
Bremen	Bremen Hbf	700800	10	0
Hamburg	Hamburg Hbf	840960	12	0
Hannover	Hannover Hbf	840960	12	0
Leipzig	Hauptbahnhof Leipzig	560640	24	1
Frankfurt Am Main	Frankfurt am Main Hauptbahnhof	677440	29	1
Saarbrücken	Saarbrücken Hbf	1261440	18	0
Karlsruhe	Karlsruhe Hbf	981120	14	0
Mannheim	Mannheim Hbf	630720	9	0
Berlin	Berlin Hbf	1121280	16	0
Dresden	Dresden Hbf	1121280	16	0
Stuttgart	Stuttgart Hbf	397120	17	1
Munich	München Ost	981120	14	0
Copenhagen	København Hovedbanegård	490560	7	0
Tallinn	Tallinn Station	210240	9	1
Thessaloniki	Thessaloniki Station	163520	7	1
Athens	Athens Station	93440	4	1
Sevilla	Sevilla-Santa Justa	840960	12	0
Valencia	Valencia-Joaquín Sorolla	210240	9	1
Zaragoza	Zaragoza Delicias	700800	10	0
Barcelona	Barcelona-Sants	981120	14	0
Bilbao	Bilbao Abando	186880	8	1
Madrid	Madrid Chamartín	1471680	21	0

Table C.4: Railway stations capacity data (table 2/2).
Retrieved by manual inspection of OpenRailwayMap ((Matheisen et al., 2024).

AREA	NAME	Cap_Station (2050)	Tracks	Terminus
Madrid	Madrid Atocha	1681920	24	0
Helsinki	Helsinki Central Station	1331520	19	0
Porto	Porto Campanha	1051200	15	0
Cluj-Napoca	Cluj-Napoca Station	560640	8	0
Bucharest	Gara Bucuresti Nord	327040	14	1
Gothenburg	Goteborgs Central	1121280	16	0
Stockholm	Stockholm Central	1261440	18	0
Ljubljana	Ljubljana Station	630720	9	0
Ankara	Ankara Station	770880	11	0
London	Euston Station	420480	18	1
London	St Pancras International	303680	13	1
London	King's Cross	256960	11	1
Birmingham	Birmingham Curzon Street	163520	7	1
Liverpool	Liverpool Lime Street	233600	10	1
Manchester	Manchester Picadilly Circus	981120	14	0
Newcastle Upon Tyne	Newcastle Station	840960	12	0
Edinburgh	Edinburgh Waverley	1401600	20	0
Glasgow	Glasgow Central	397120	17	1
Oslo	Oslo Sentralstasjon	1331520	19	0
Venice	Venezia Santa Lucia	513920	22	1
Verona	Verona Porta Nuova	630720	9	0
Milano	Milano Centrale	560640	24	1
Turin	Torino Porto Nuova	467200	20	1
Genoa	Genova Piazza Principale	700800	10	0
Bologna	Bologna Centrale	1822080	26	0
Florence	Firenze Santa Maria Novella	350400	15	1
Bari	Bari Centrale	467200	20	1
Napoli	Napoli Centrale	1752000	25	0
Vilnius	Vilnius Station	560640	8	0
Riga	Riga Central Station	490560	7	0
Amsterdam	Amsterdam Zuid	280320	4	0
Rotterdam	Rotterdam Centraal	911040	13	0
Warsaw	Warsaw Central Station	560640	8	0
Lodz	Lodz Fabryczna	560640	8	0
Poznan	Poznan Main Station	1121280	16	0
Wroclaw	Wroclaw Main Station	700800	10	0
Katowice	Katowice Station	560640	8	0
Istanbul	Istanbul Sirkeci Station	490560	7	0
Munich	Munchen Hbf	747520	32	1
Turin	Torino Porta Susa	420480	6	0
Rome	Roma Termini	747520	32	1
Rome	Rome Tiburtina	1401600	20	0
Budapest	Budapest Nyugati	397120	17	1
Budapest	Budapest Déli	280320	12	1
Lille	Gare Lille-Europe	420480	6	0

C.3. Bottleneck details

The following details were printed from Python for the set of 14 bottlenecks. The context of the elements per node is provided in chapter 5.

Node 138 with high saturation: 'lat': 50.84477698441236, 'lon': 4.358924000120572, 'is_station': True, 'AREA': 'Brussels', 'fid': 28.0, 'ACC_TIME': 0.479, 'NAME': 'Station Brussel-Centraal', 'origin/termin': 7321113, 'traverse': 65381443, 'total_p': 72702556, 'LD_Demand': 216376, 'Cap_Station': 420480, 'Com_Demand': 107570, 'Saturation': 0.7704210814778047

Node 371 with high saturation: 'lat': 48.88164248196289, 'lon': 2.3561605001147643, 'is_station': True, 'AREA': 'Paris', 'fid': 4.0, 'ACC_TIME': 0.737, 'NAME': 'Gare du Nord', 'origin/termin': 6944238, 'traverse': 22781065, 'total_p': 29725303, 'LD_Demand': 88468, 'Cap_Station': 747520, 'Com_Demand': 1031188, 'Saturation': 1.4978277042408208

Node 372 with high saturation: 'lat': 48.8441379819448, 'lon': 2.373991499752425, 'is_station': True, 'AREA': 'Paris', 'fid': 6.0, 'ACC_TIME': 0.683, 'NAME': 'Gare du Lyon', 'origin/termin': 9543110, 'traverse': 10869262, 'total_p': 20412372, 'LD_Demand': 60751, 'Cap_Station': 513920, 'Com_Demand': 536926, 'Saturation': 1.1629769419959761

Node 421 with high saturation: 'lat': 50.638929867803306, 'lon': 3.075665091253841, 'is_station': True, 'AREA': 'Lille', 'fid': 144.0, 'ACC_TIME': 0.431, 'NAME': 'Gare Lille-Europe', 'origin/termin': 6073449, 'traverse': 105403159, 'total_p': 111476609, 'LD_Demand': 331775, 'Cap_Station': 420480, 'Com_Demand': 92989, 'Saturation': 1.0101898404556306

Node 431 with high saturation: 'lat': 50.63603553096487, 'lon': 3.0721798487116643, 'is_station': True, 'AREA': 'Lille', 'fid': 2.0, 'ACC_TIME': 0.435, 'NAME': 'Gare Lille-Flandres', 'origin/termin': 5839539, 'traverse': 12014494, 'total_p': 17854033, 'LD_Demand': 53137, 'Cap_Station': 397120, 'Com_Demand': 289211, 'Saturation': 0.8620769638267242

Node 569 with high saturation: 'lat': 50.9437834845222, 'lon': 6.95681999963652, 'is_station': True, 'AREA': 'Cologne', 'fid': 39.0, 'ACC_TIME': 0.881, 'NAME': 'Köln Hbf', 'origin/termin': 8758649, 'traverse': 49657727, 'total_p': 58416376, 'LD_Demand': 173858, 'Cap_Station': 770880, 'Com_Demand': 481218, 'Saturation': 0.8497772199235971

Node 616 with high saturation: 'lat': 49.479592482998804, 'lon': 8.46587700037291, 'is_station': True, 'AREA': 'Mannheim', 'fid': 49.0, 'ACC_TIME': 0.714, 'NAME': 'Mannheim Hbf', 'origin/termin': 8548972, 'traverse': 47591840, 'total_p': 56140813, 'LD_Demand': 167085, 'Cap_Station': 630720, 'Com_Demand': 325693, 'Saturation': 0.7812955900821714

Node 673 with high saturation: 'lat': 50.10651148381418, 'lon': 8.660266499873845, 'is_station': True, 'AREA': 'Frankfurt Am Main', 'fid': 46.0, 'ACC_TIME': 0.977, 'NAME': 'Frankfurt am Main Hauptbahnhof', 'origin/termin': 5231840, 'traverse': 5134281, 'total_p': 10366122, 'LD_Demand': 30851, 'Cap_Station': 677440, 'Com_Demand': 842722, 'Saturation': 1.2895216642289946 Node 684 with high saturation: 'lat': 48.786013391150306, 'lon': 9.183900901808954, 'is_station': True, 'AREA': 'Stuttgart', 'fid': 53.0, 'ACC_TIME': 0.678, 'NAME': 'Stuttgart Hbf', 'origin/termin': 19755340, 'traverse': 30864178, 'total_p': 50619519, 'LD_Demand': 150653, 'Cap_Station': 397120, 'Com_Demand': 355383, 'Saturation': 1.2742655378603123

Node 956 with high saturation: 'lat': 43.77673147326863, 'lon': 11.247903000429966, 'is_station': True, 'AREA': 'Florence', 'fid': 102.0, 'ACC_TIME': 0.486, 'NAME': 'Firenze Santa Maria Novella', 'origin/termin': 8193807, 'traverse': 36311286, 'total_p': 44505093, 'LD_Demand': 132455, 'Cap_Station': 350400, 'Com_Demand': 133256, 'Saturation': 0.7583094656066021

Node 1113 with high saturation: 'lat': 52.340396486037776, 'lon': 4.875108500162072, 'is_station': True, 'AREA': 'Amsterdam', 'fid': 113.0, 'ACC_TIME': 0.538, 'NAME': 'Amsterdam Zuid', 'origin/termin': 12245882, 'traverse': 5599652, 'total_p': 17845534, 'LD_Demand': 53111, 'Cap_Station': 280320,

'Com_Demand': 200465, 'Saturation': 0.904597277847697

Node 1650 with high saturation: 'lat': 51.5288890303063, 'lon': -0.1344100004447032, 'is_station': True, 'AREA': 'London', 'fid': 82.0, 'ACC_TIME': 1.035, 'NAME': 'Euston Station', 'origin/termin': 30064846, 'traverse': 29611412, 'total_p': 59676259, 'LD_Demand': 177607, 'Cap_Station': 420480, 'Com_Demand': 140776, 'Saturation': 0.7571915773015655

Node 1654 with high saturation: 'lat': 51.53117678311797, 'lon': -0.12322205657058019, 'is_station': True, 'AREA': 'London', 'fid': 84.0, 'ACC_TIME': 1.036, 'NAME': "King's Cross", 'origin/termin': 29723861, 'traverse': 7803948, 'total_p': 37527809, 'LD_Demand': 111689, 'Cap_Station': 256960, 'Com_Demand': 143997, 'Saturation': 0.9950455652642719

Node 1655 with high saturation: 'lat': 51.53207066753262, 'lon': -0.1265945043991518, 'is_station': True, 'AREA': 'London', 'fid': 83.0, 'ACC_TIME': 1.037, 'NAME': 'St Pancras International', 'origin/termin': 30305980, 'traverse': 72859525, 'total_p': 103165505, 'LD_Demand': 307040, 'Cap_Station': 303680, 'Com_Demand': 40354, 'Saturation': 1.1439482230506997

There are 14 stations that are at risk of being a bottleneck in 2050.

D

Experiment Networks & Results

This appendix provides a comprehensive overview of the experiments and results associated with chapter 6. The chapter begins with a complete overview of the passenger welfare effects from the experiments in section D.1. Following this, the network layouts for the station relocation experiment set are presented per type of experiment. The figures presented in these sections are created with QGIS, 2023 and include urban centers (GHS) from Schiavina et al. (2019).

D.1. Overview of experiment results

This research has executed three types of experiments. These three are abbreviated to Q2, Q3 and Q4, referring to the respective research questions that are answered by them. The research questions can be found in section 1.6. Table D.1 contains the passenger welfare effects that are generated by existing peripheral stations (Q2) and by relocating HSR-services to an airport station (Q3).

Table D.1: Passenger welfare effect results of experiment set Q2 and Q3.

ID	City	$\sum$ CS 2050; PO [million €/year]	$\sum$ CS 2050; Both [million €/year]	$\sum$ CS 2024; PO [million €/year]	$\sum$ CS 2024; Both [million €/year]
Q2.1	Birmingham	226	235	81	85
Q2.2	Brussels	-323	-32	-117	-12
Q2.3	Copenhagen	106	74	38	27
Q2.4	Frankfurt	517	443	187	160
Q2.5	Leipzig	-35	-4	-13	-2
Q2.6	Lyon	255	326	92	118
Q2.7	Montpellier	103	93	37	34
Q2.8	Paris	925	820	334	296
Q2.9	Vienna	-317	-55	-114	-20
Q3.1	Amsterdam	115	68	41	25
Q3.2	Budapest	43	66	15	24
Q3.3	Cologne	n/a	30	n/a	11
Q3.4	Lille	514	492	185	178
Q3.5	London	n/a	-235	n/a	-85
Q3.6	Stuttgart	-37	12	-13	4

Table D.2 contains the results of the strategic relocation experiment (Q4). The aim of this research question was to quantify the passenger welfare effects of relocating HSR-services to various locations, and by doing so finding out which maximises the passenger welfare effects. These various relocation alternatives are defined by the four cardinal wind-directions (N, E, S, W) and the four inter-cardinal wind-directions (NE, SE, SW, NW), as has been described in chapter 6. The relocation alternatives that lead to the highest total consumer surplus per year, or most positive passenger welfare effects, are presented in bold text.

Table D.2: Passenger welfare effect results of experiment set Q4.

ID	City	Σ CS 2050; Both [million €/year]	Σ CS 2024; Both [million €/year]
Q4.1	Amsterdam S	-22	-8
Q4.1	Amsterdam SW	-59	-21
Q4.2	Brussels E	28	10
Q4.2	Brussels NE	-85	-31
Q4.2	Brussels NW	-68	-25
Q4.2	Brussels SE	117	42
Q4.2	Brussels SW	-33	-12
Q4.3	Budapest E	-24	-9
Q4.3	Budapest N	-7	-3
Q4.3	Budapest NE	12	4
Q4.3	Budapest NW	41	15
Q4.3	Budapest S	58	21
Q4.3	Budapest SE	26	9
Q4.3	Budapest W	51	18
Q4.4	Cologne E	7	3
Q4.4	Cologne NE	-24	-9
Q4.4	Cologne NW	167	60
Q4.4	Cologne S	78	28
Q4.4	Cologne SW	44	16
Q4.4	Cologne W	209	75
Q4.5	Florence N	172	62
Q4.5	Florence NE	156	56
Q4.6	Frankfurt Am Main E	122	44
Q4.6	Frankfurt Am Main N	-9	-3
Q4.6	Frankfurt Am Main NE	0	0
Q4.6	Frankfurt Am Main S	190	69
Q4.6	Frankfurt Am Main SE	183	66
Q4.6	Frankfurt Am Main SW	65	23
Q4.6	Frankfurt Am Main W	-12	-4
Q4.7	Lille S	552	199
Q4.7	Lille SW	438	158
Q4.7	Lille W	262	94
Q4.8	London E	127	46
Q4.8	London N	-98	-36
Q4.8	London NE	-51	-18
Q4.8	London S	-86	-31
Q4.8	London SE	152	55
Q4.8	London SW	-238	-86
Q4.8	London W	-295	-106
Q4.9	Mannheim E	320	115
Q4.9	Mannheim N	-53	-19
Q4.9	Mannheim NW	-77	-28
Q4.9	Mannheim S	-1	0
Q4.9	Mannheim SE	208	75
Q4.9	Mannheim SW	-51	-19
Q4.9	Mannheim W	-66	-24
Q4.10	Paris E	431	156
Q4.10	Paris N	-67	-24
Q4.10	Paris NE	268	97
Q4.10	Paris NW	-58	-21
Q4.10	Paris S	-1	0
Q4.10	Paris SE	362	130
Q4.10	Paris SW	8	3
Q4.10	Paris W	-50	-18
Q4.11	Stuttgart NW	35	12
Q4.11	Stuttgart SW	14	5
Q4.11	Stuttgart W	44	16

D.2. Q2 Experiments: Peripheral stations in base network

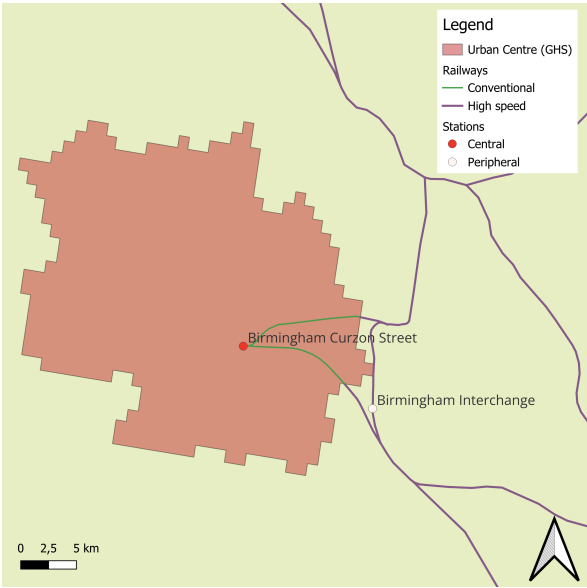


Figure D.1: Q2 Experiment 1: Birmingham

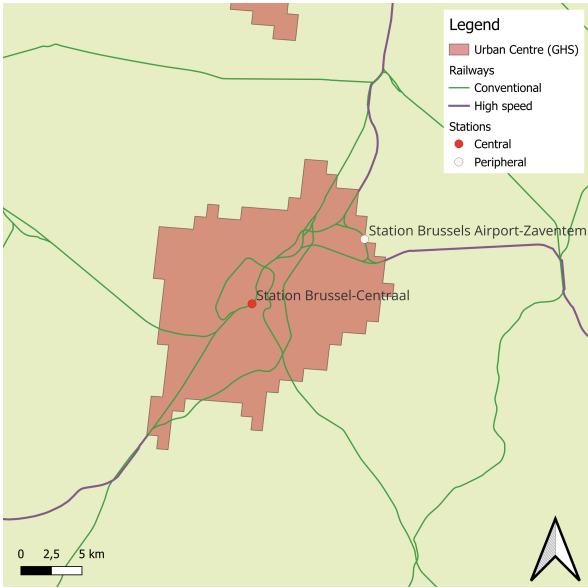


Figure D.2: Q2 Experiment 2: Brussels

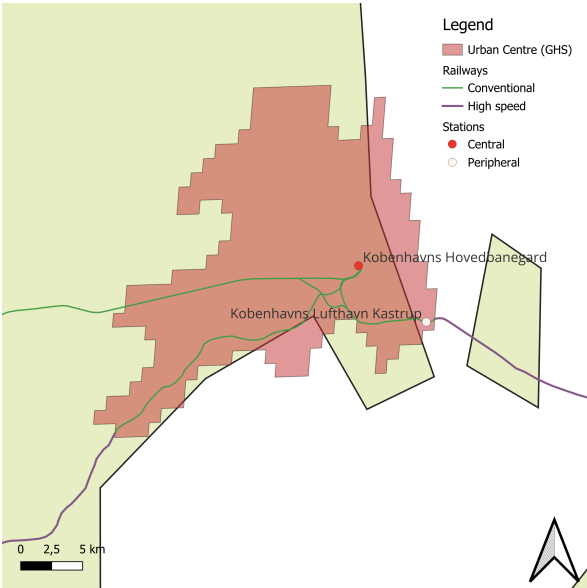


Figure D.3: Q2 Experiment 3: Copenhagen

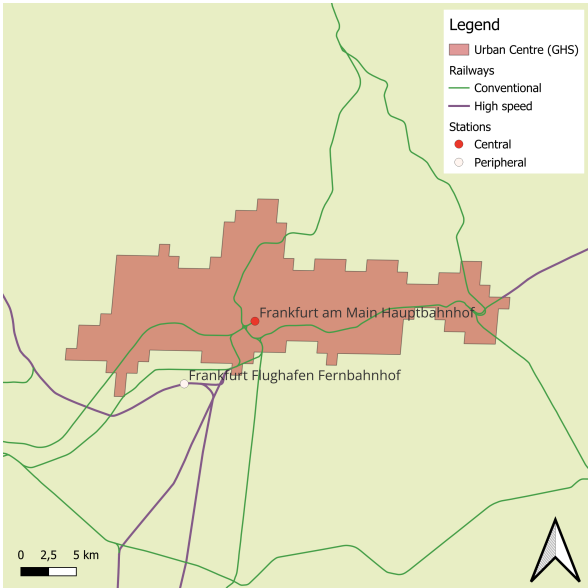


Figure D.4: Q2 Experiment 4: Frankfurt

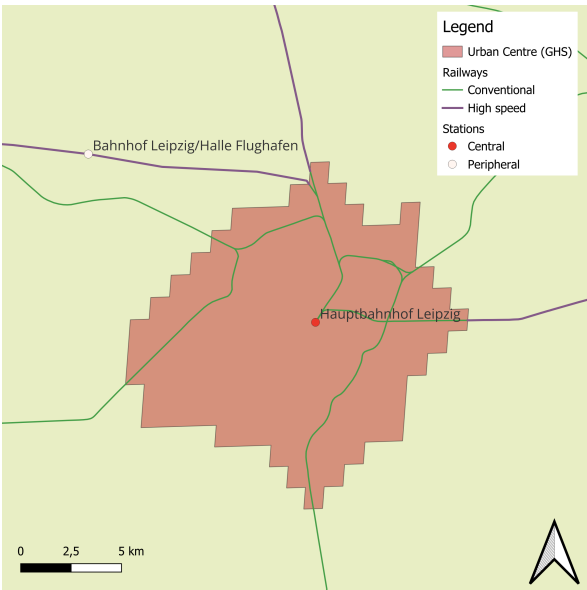


Figure D.5: Q2 Experiment 5: Leipzig

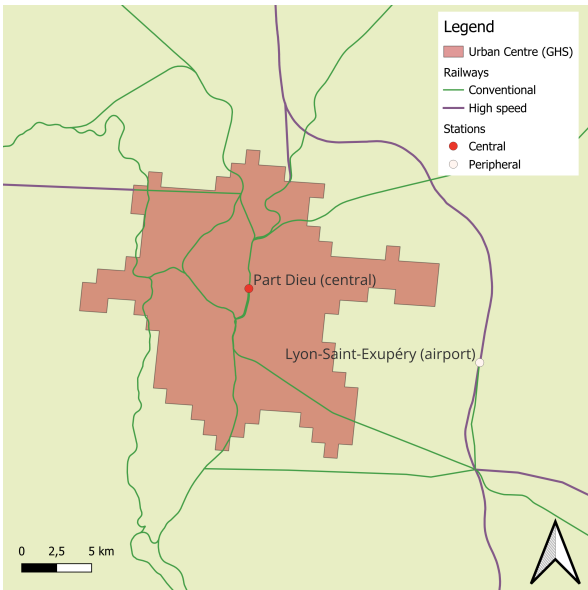


Figure D.6: Q2 Experiment 6: Lyon

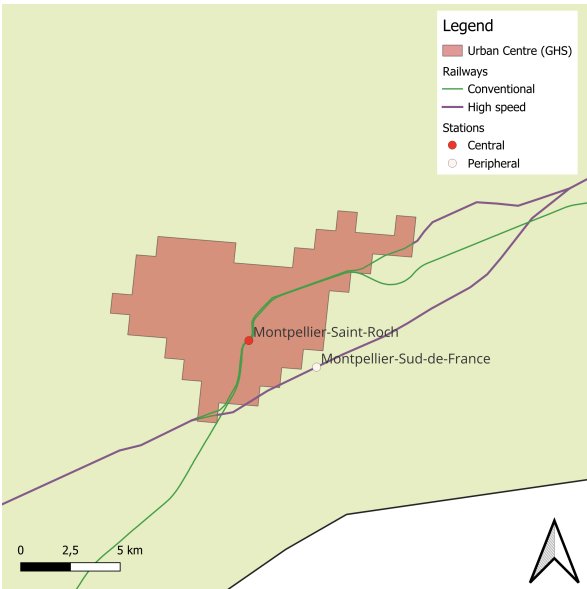


Figure D.7: Q2 Experiment 7: Montpellier

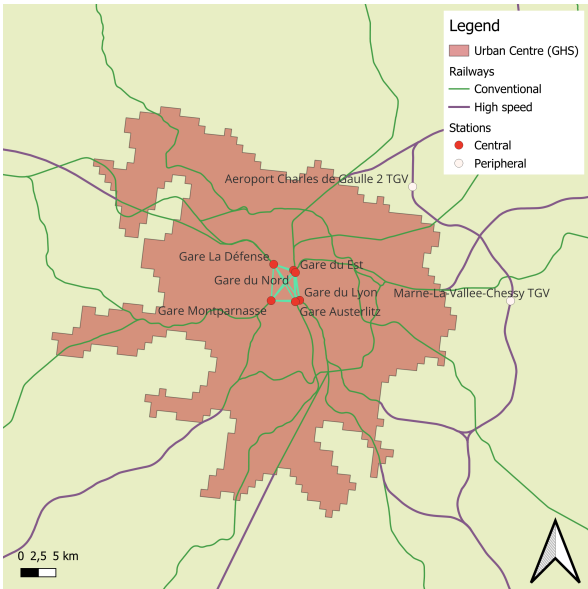


Figure D.8: Q2 Experiment 8: Paris

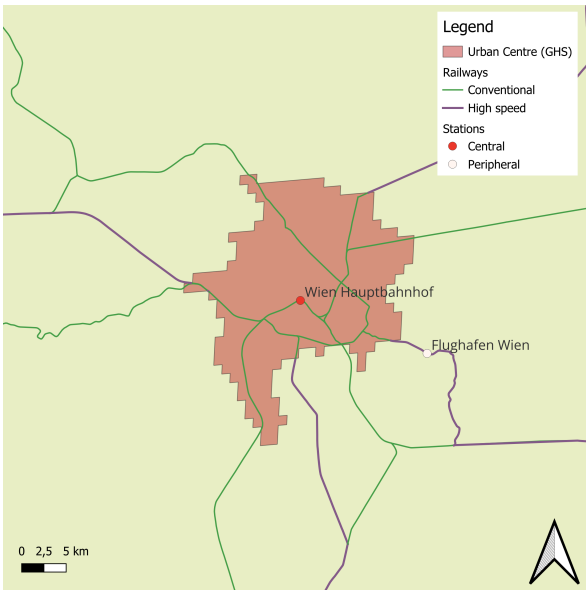


Figure D.9: Q2 Experiment 9: Vienna

D.3. Q3 Experiments: Relocation to airport

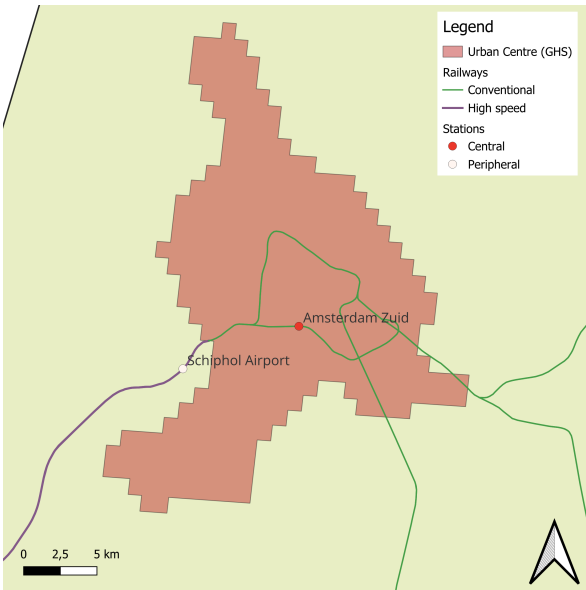


Figure D.10: Q3 Experiment 1: Amsterdam

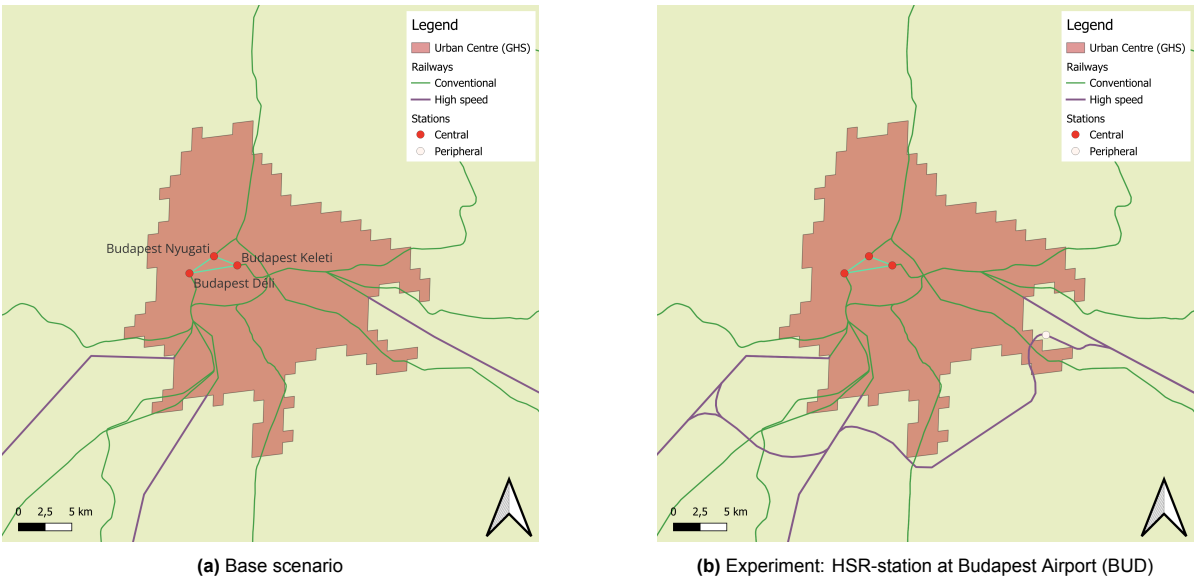


Figure D.11: Q3 Experiment 2: Budapest

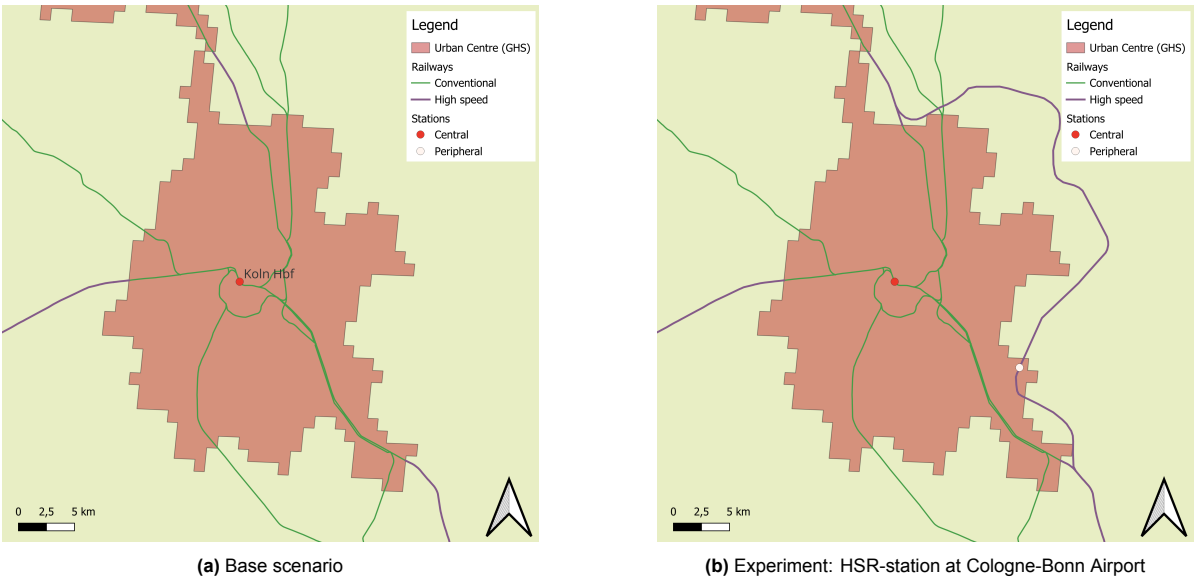


Figure D.12: Q3 Experiment 3: Cologne

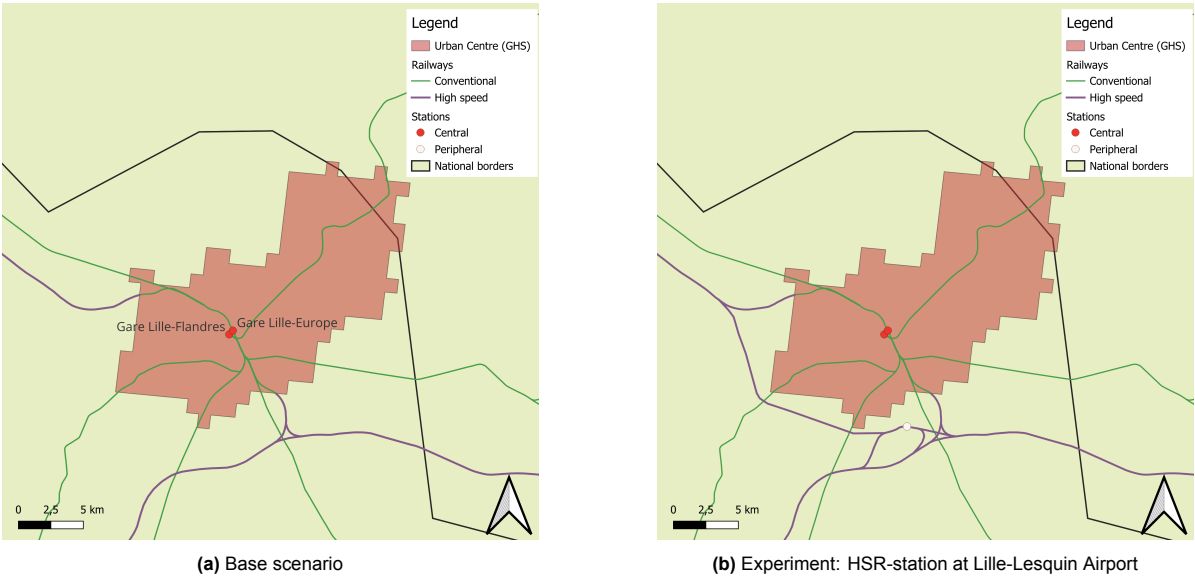


Figure D.13: Q3 Experiment 4: Lille

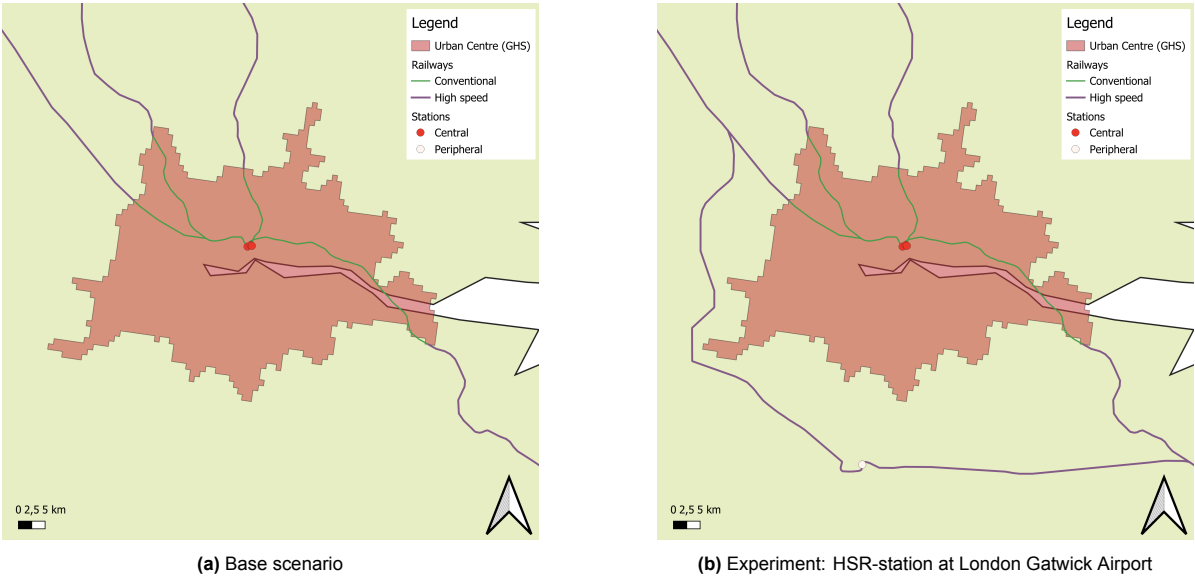


Figure D.14: Q3 Experiment 5: London

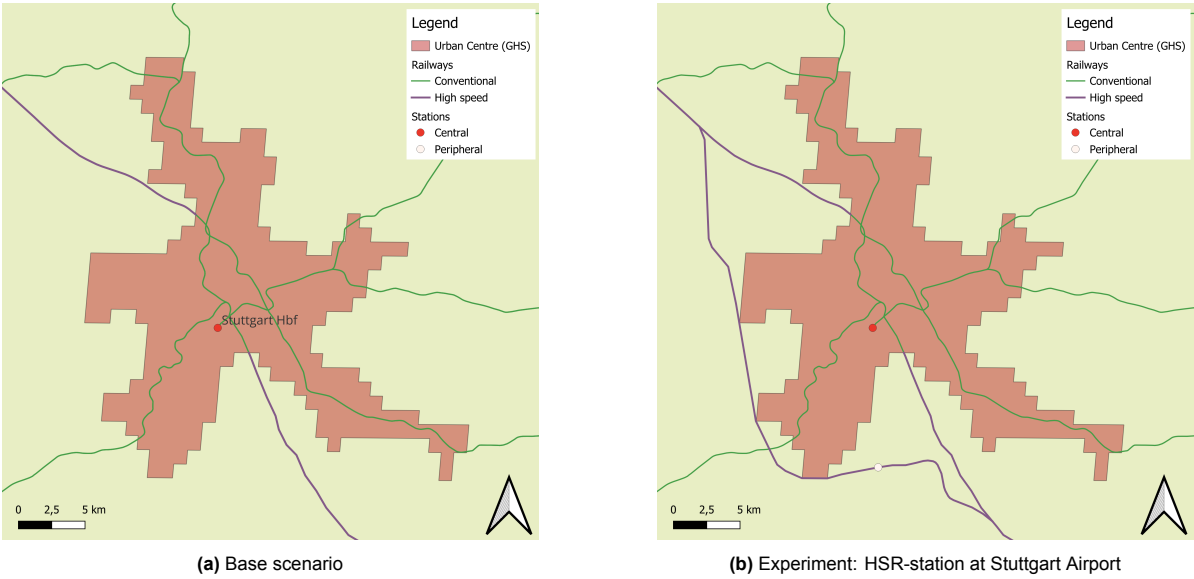


Figure D.15: Q3 Experiment 6: Stuttgart

D.4. Q4 Experiments: Strategic relocation

D.4.1. Amsterdam

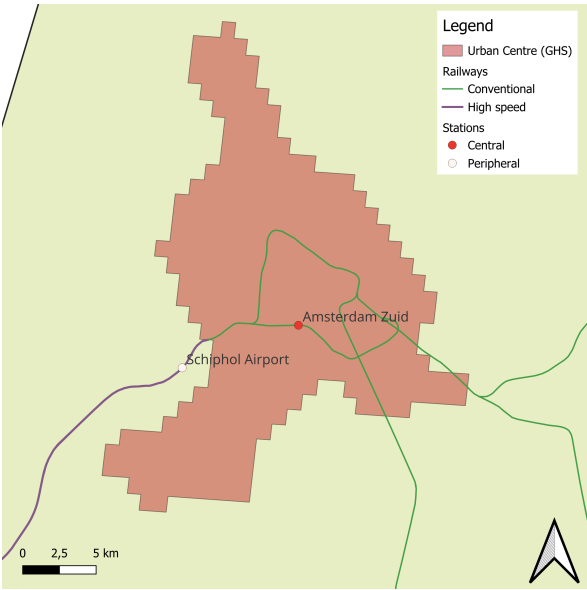


Figure D.16: Q4 Experiment 1
Amsterdam base scenario

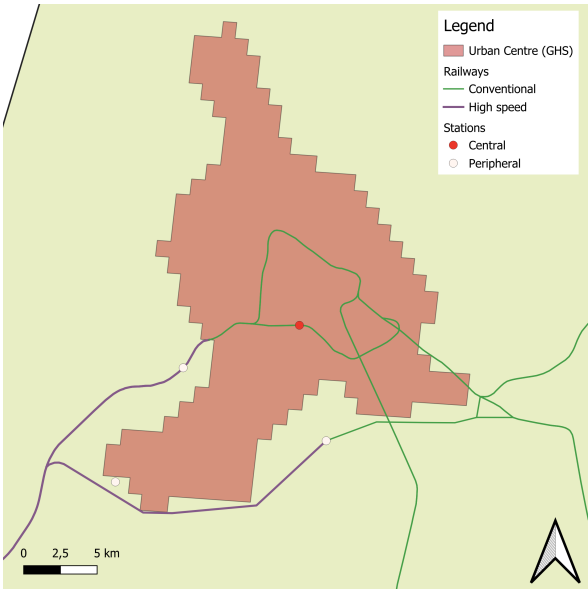


Figure D.17: Q4 Experiment 1
Amsterdam station S

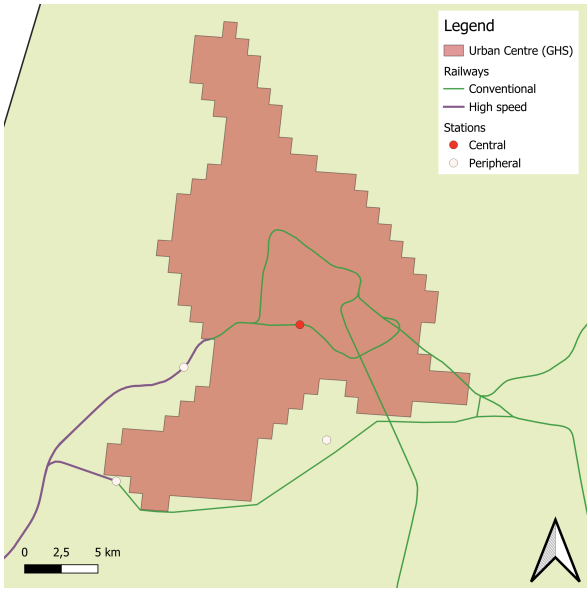


Figure D.18: Q4 Experiment 1
Amsterdam station SW

D.4.2. Brussels

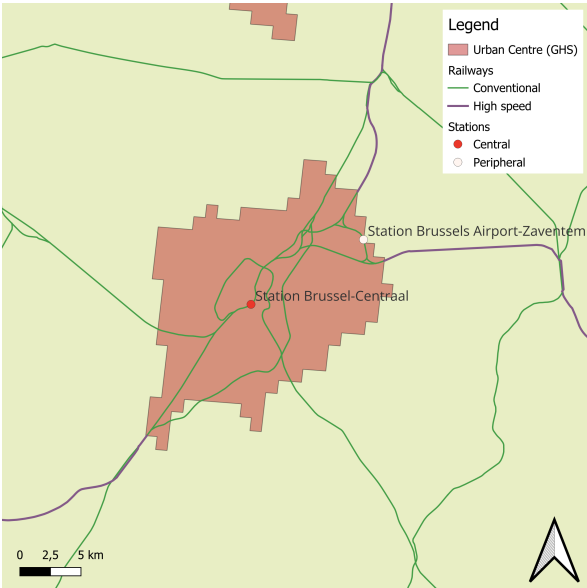


Figure D.19: Q4 Experiment 2
Brussels base scenario

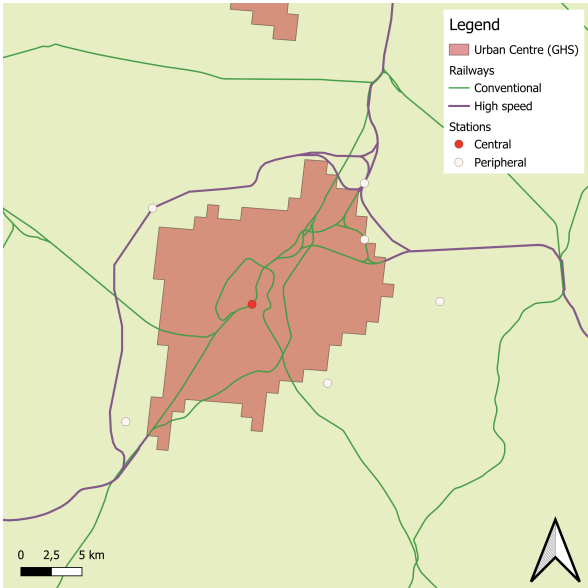


Figure D.20: Q4 Experiment 2
Brussels station NE

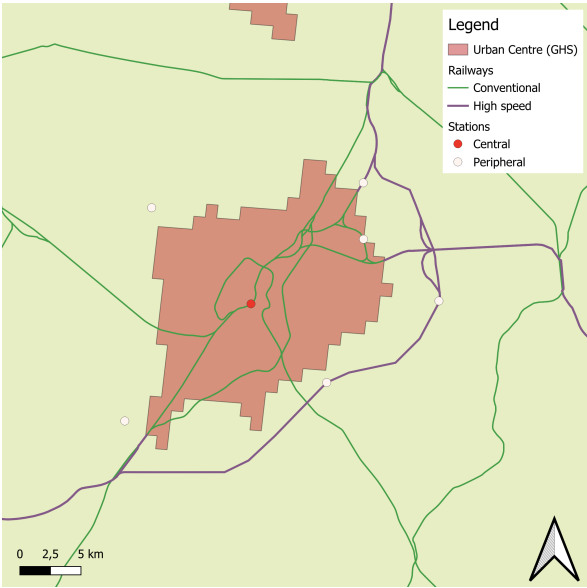


Figure D.21: Q4 Experiment 2
Brussels station E

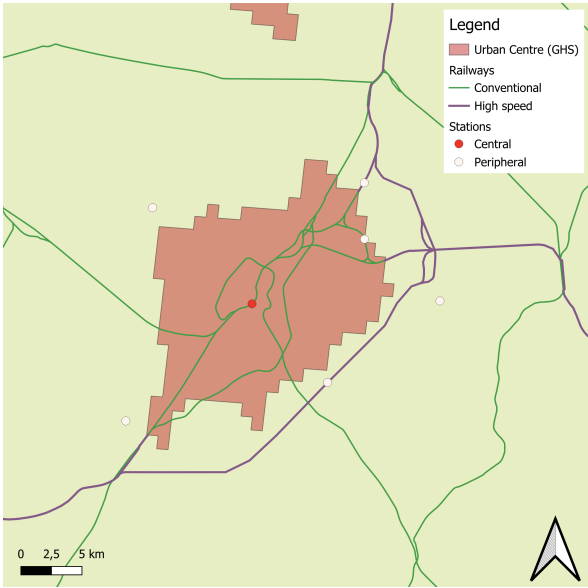


Figure D.22: Q4 Experiment 2
Brussels station SE

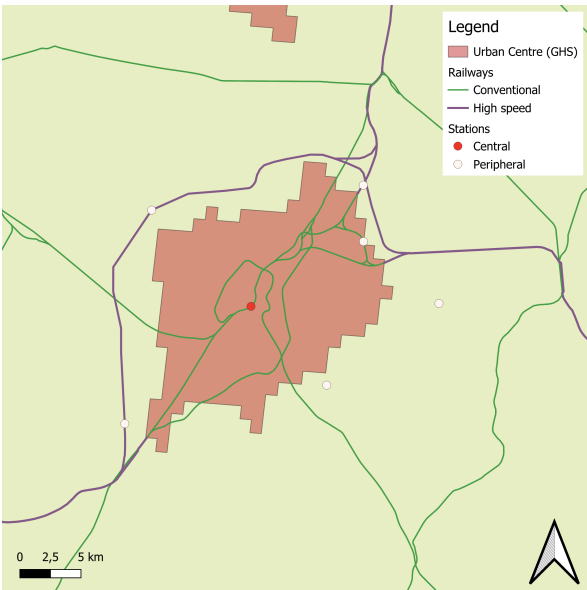


Figure D.23: Q4 Experiment 2
Brussels station SW

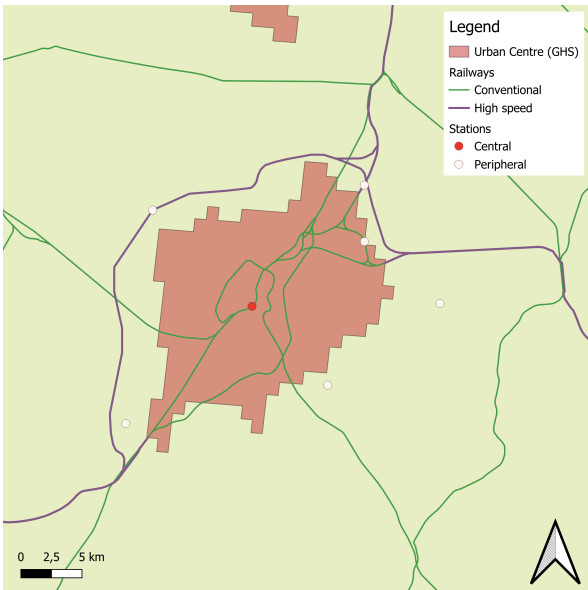


Figure D.24: Q4 Experiment 2
Brussels station NW

D.4.3. Budapest

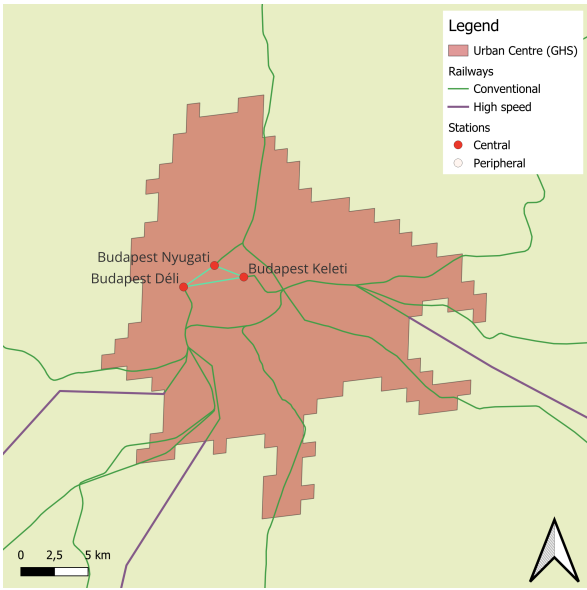


Figure D.25: Q4 Experiment 3
Budapest base scenario

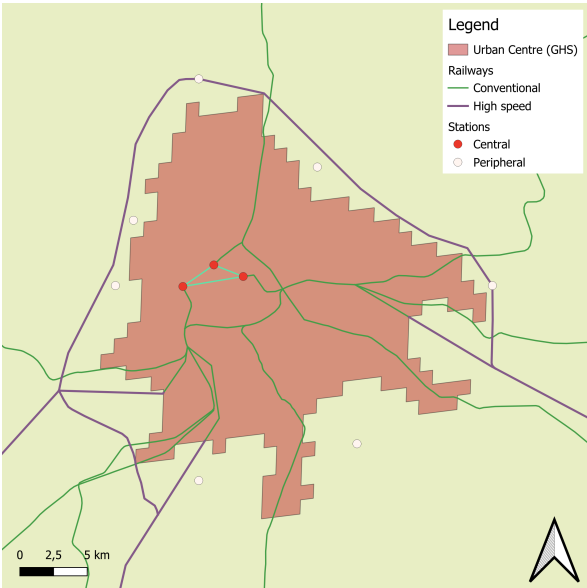


Figure D.26: Q4 Experiment 3
Budapest station N and station E scenario

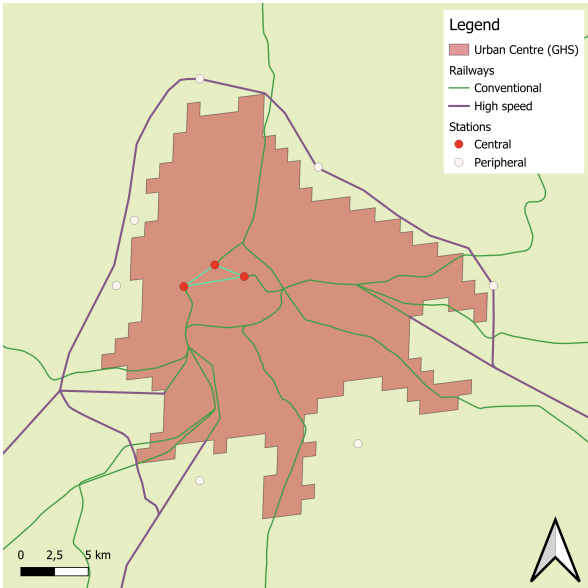


Figure D.27: Q4 Experiment 3
Budapest station NE

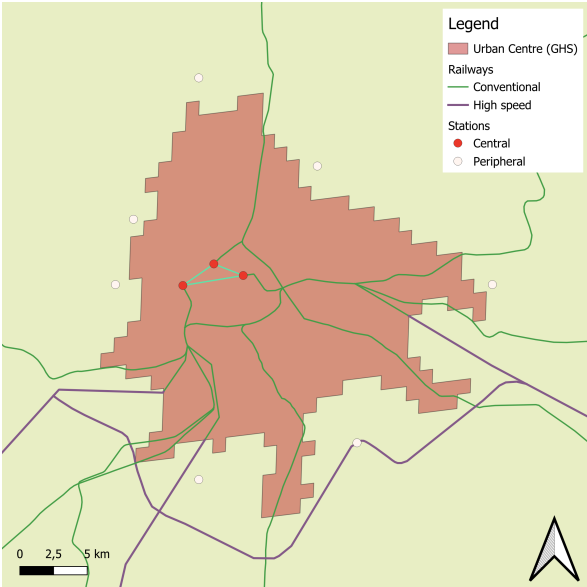


Figure D.28: Q4 Experiment 3
Budapest station SE

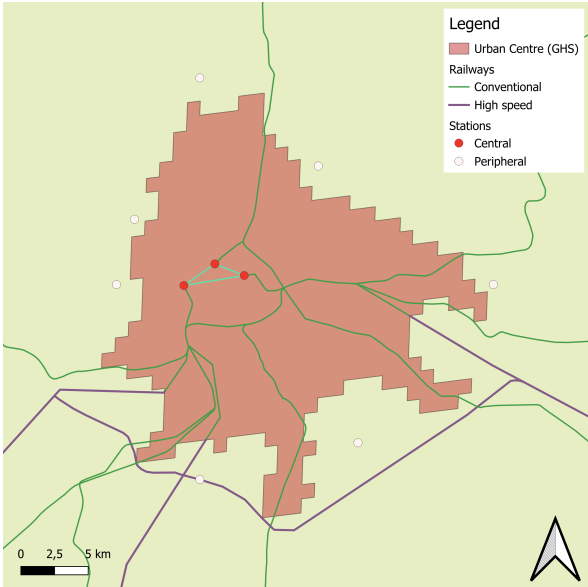


Figure D.29: Q4 Experiment 3
Budapest station S

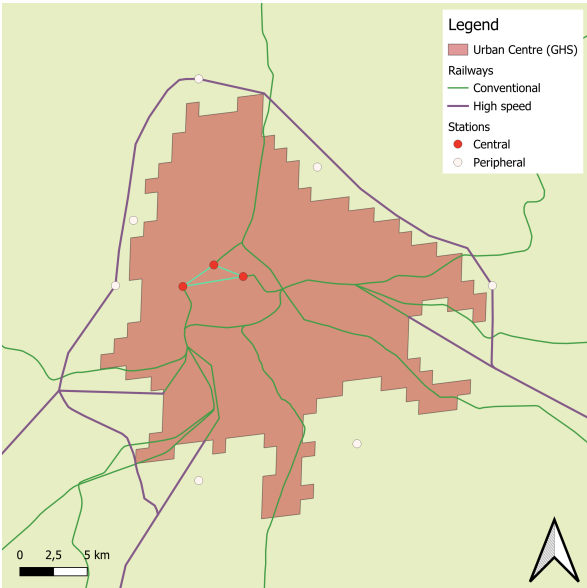


Figure D.30: Q4 Experiment 3
Budapest station W

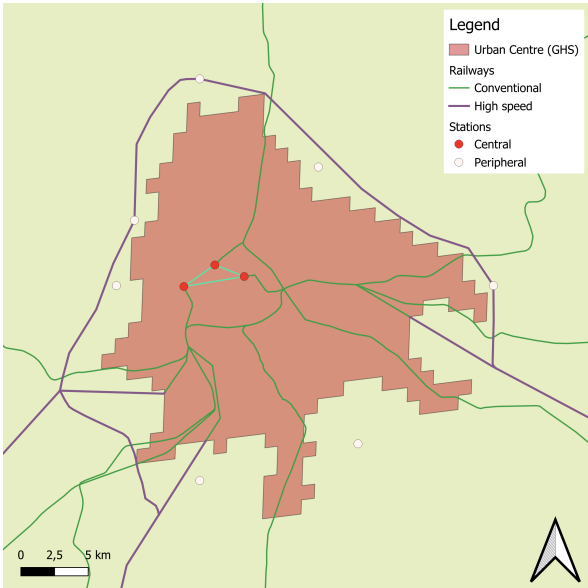


Figure D.31: Q4 Experiment 3
Budapest station NW

D.4.4. Cologne

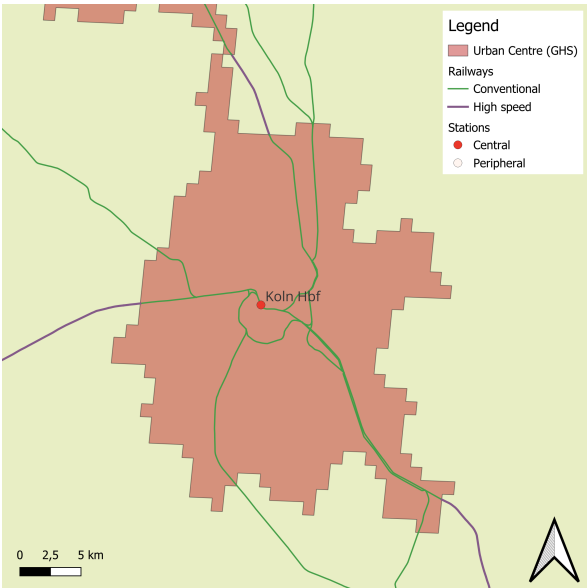


Figure D.32: Q4 Experiment 4
Cologne base scenario

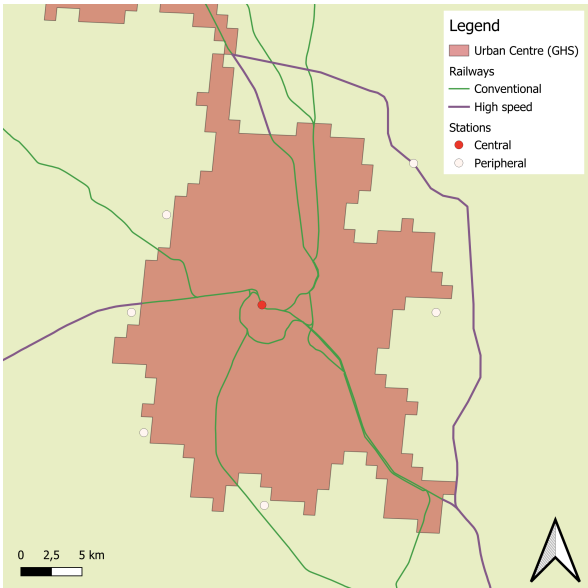


Figure D.33: Q4 Experiment 4
Cologne station NE

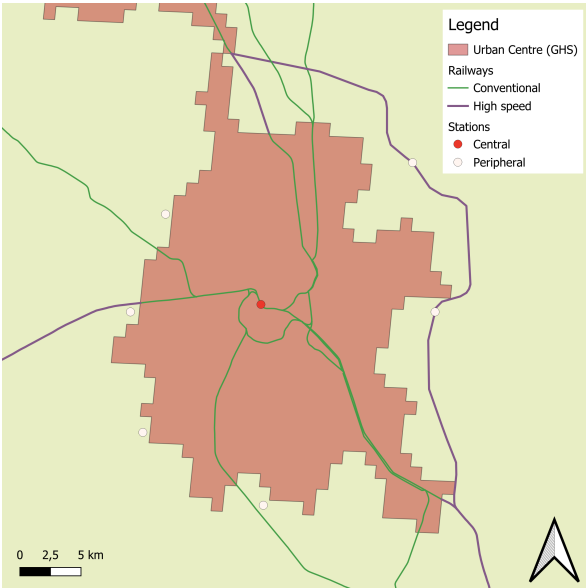


Figure D.34: Q4 Experiment 4
Cologne station E

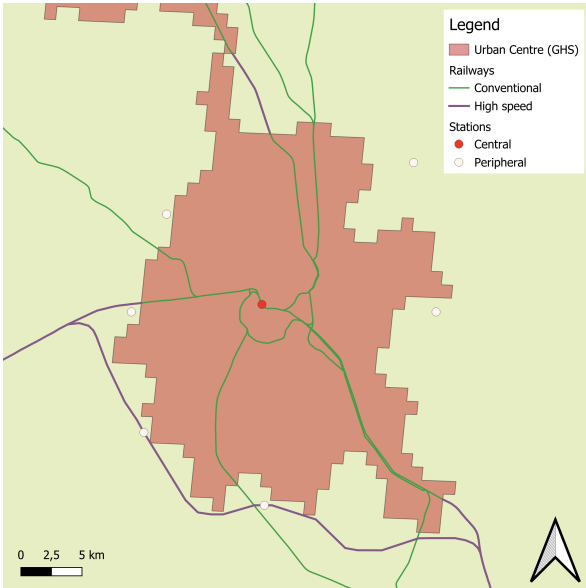


Figure D.35: Q4 Experiment 4
Cologne station S

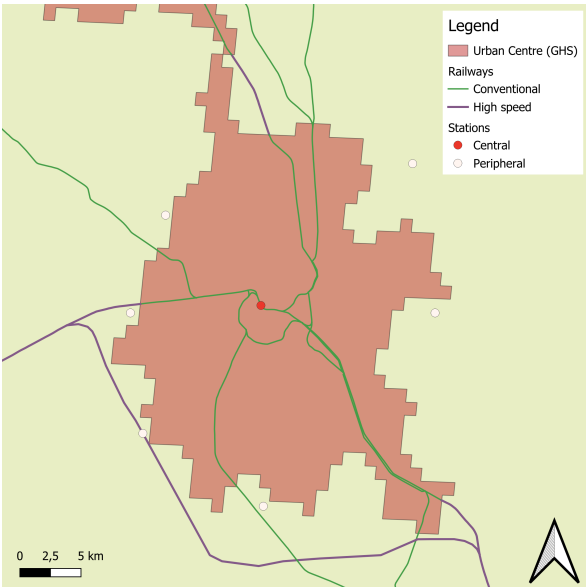


Figure D.36: Q4 Experiment 4
Cologne station SW

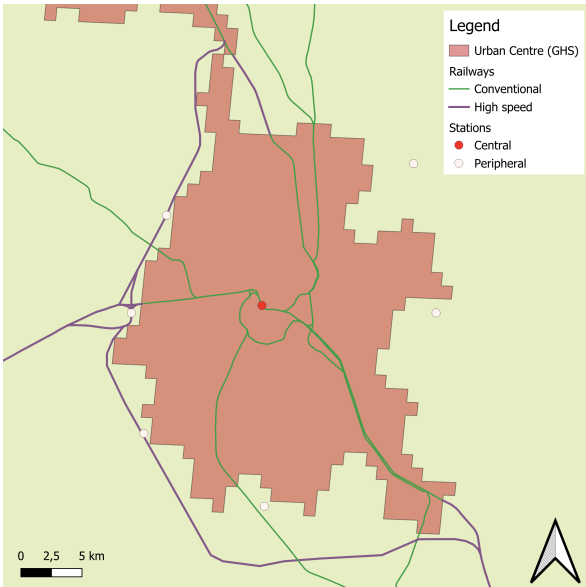


Figure D.37: Q4 Experiment 4
Cologne station W

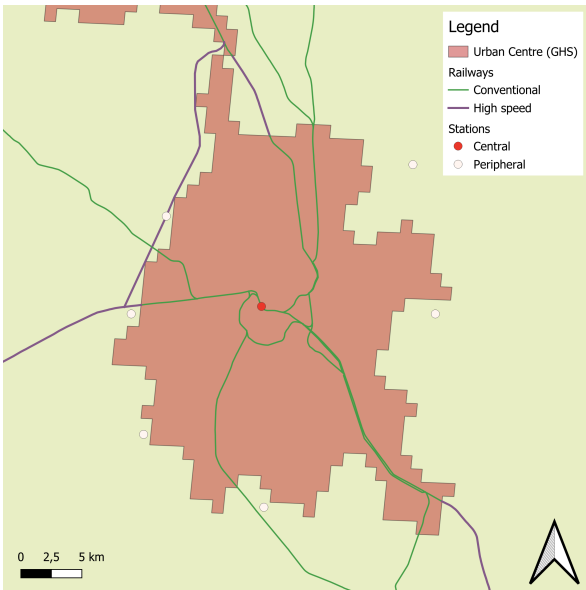


Figure D.38: Q4 Experiment 4
Cologne station NW

D.4.5. Florence

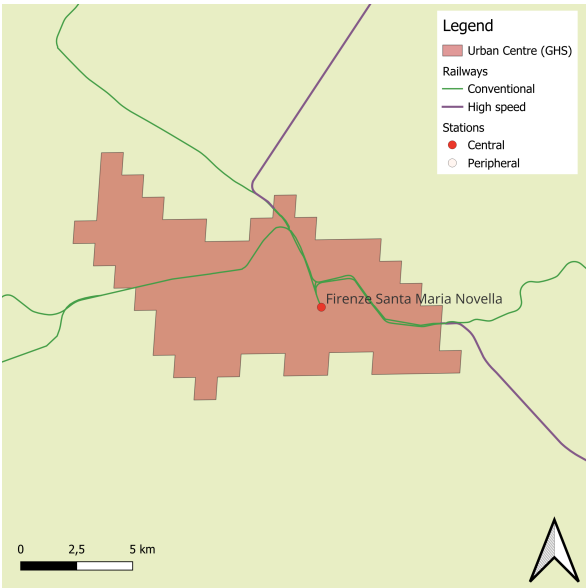


Figure D.39: Q4 Experiment 5
Florence base scenario

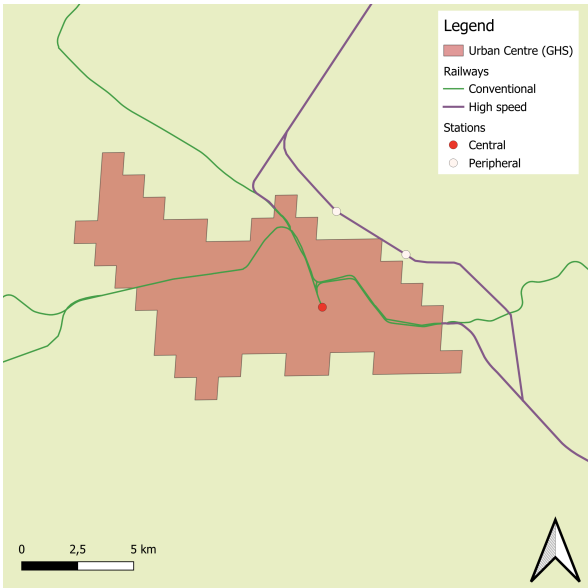


Figure D.40: Q4 Experiment 5
Florence station N and station NE scenario

D.4.6. Frankfurt Am Main

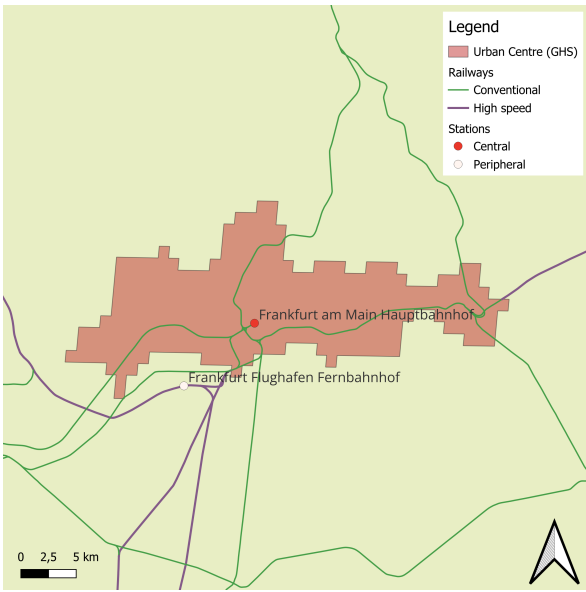


Figure D.41: Q4 Experiment 6
Frankfurt Am Main base scenario

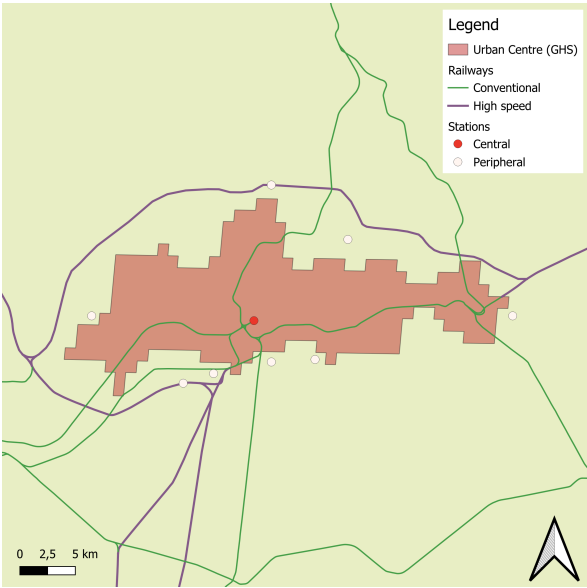


Figure D.42: Q4 Experiment 6
Frankfurt Am Main station N

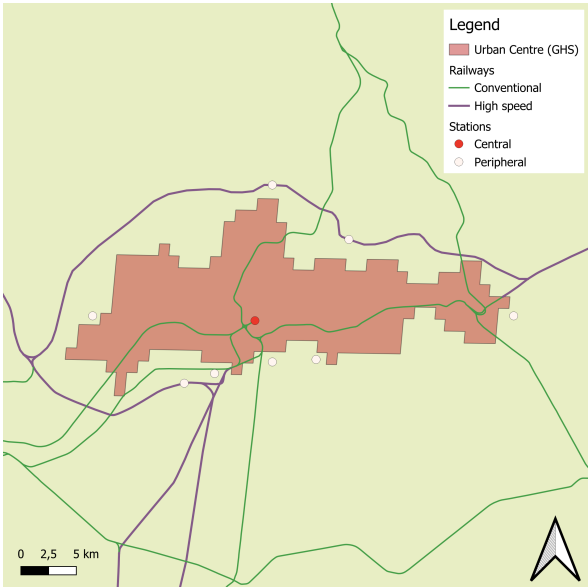


Figure D.43: Q4 Experiment 6
Frankfurt Am Main station NE

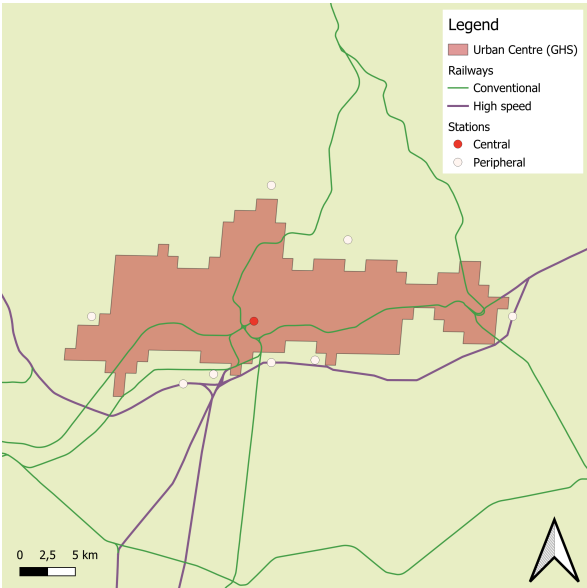


Figure D.44: Q4 Experiment 6
Frankfurt Am Main station E and station S

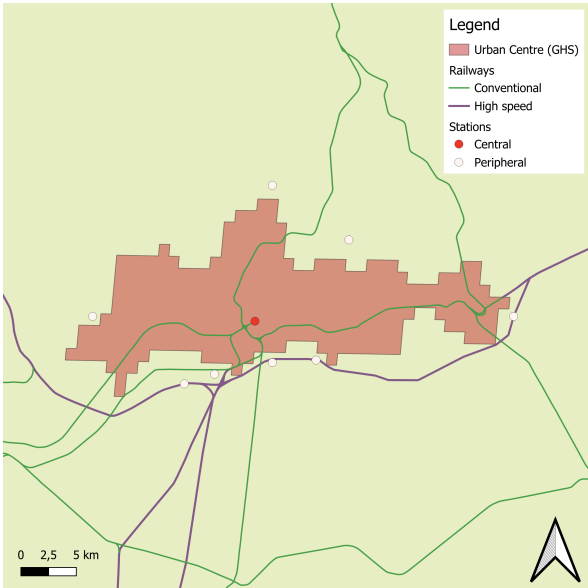


Figure D.45: Q4 Experiment 6
Frankfurt Am Main station SE

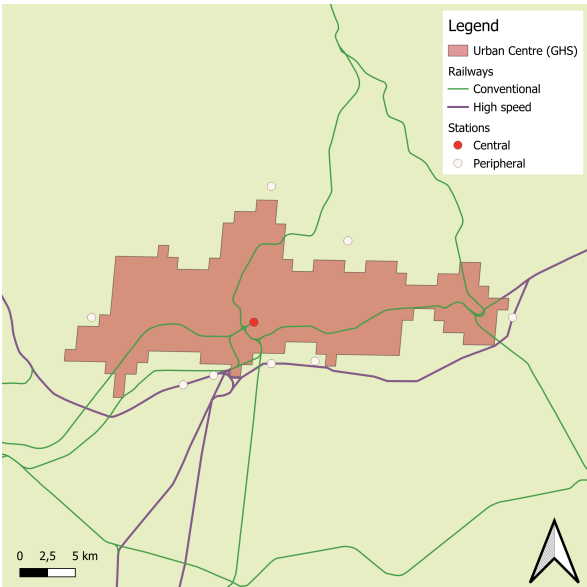


Figure D.46: Q4 Experiment 6
Frankfurt Am Main station SW

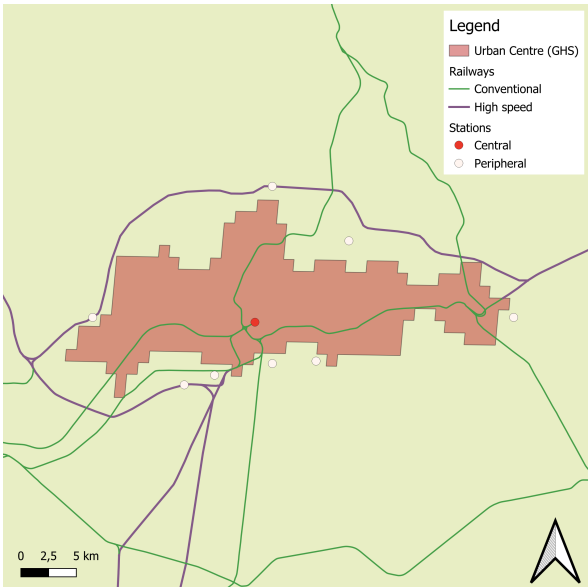


Figure D.47: Q4 Experiment 6
Frankfurt Am Main station W

D.4.7. Lille

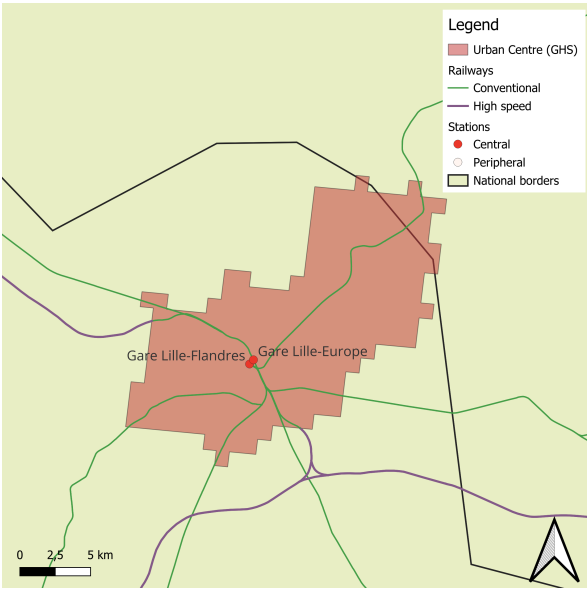


Figure D.48: Q4 Experiment 7
Lille base scenario

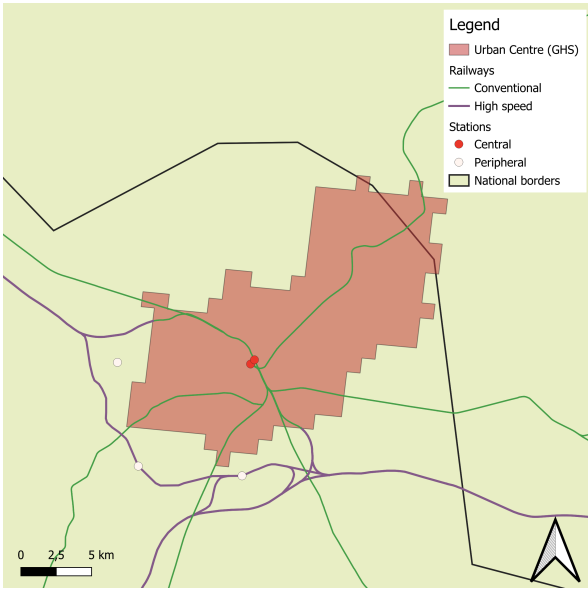


Figure D.49: Q4 Experiment 7
Lille station S

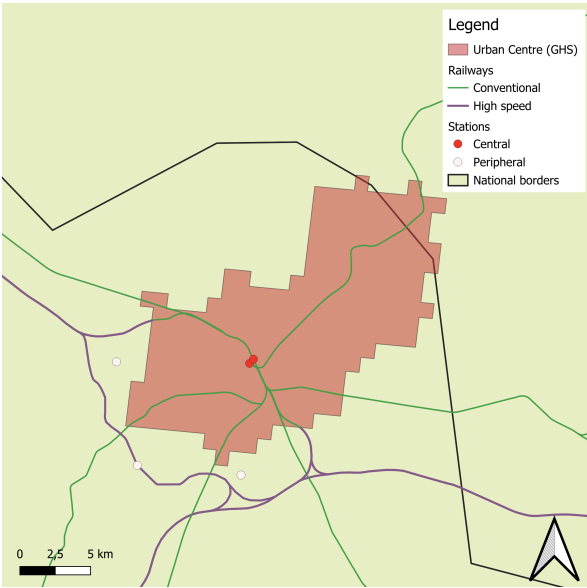


Figure D.50: Q4 Experiment 7
Lille station SW

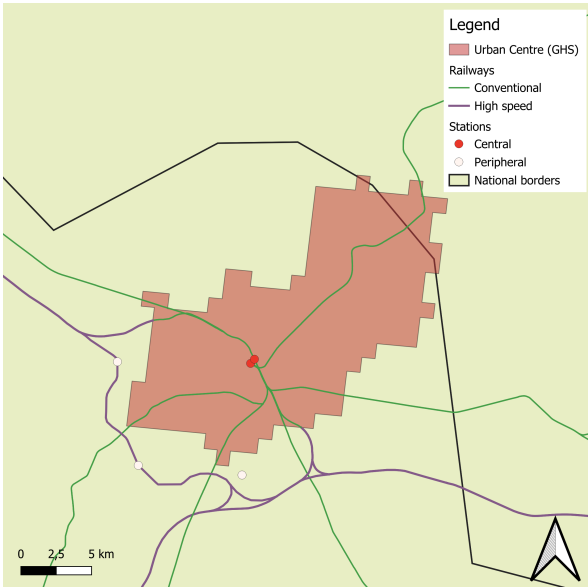


Figure D.51: Q4 Experiment 7
Lille station W

D.4.8. London

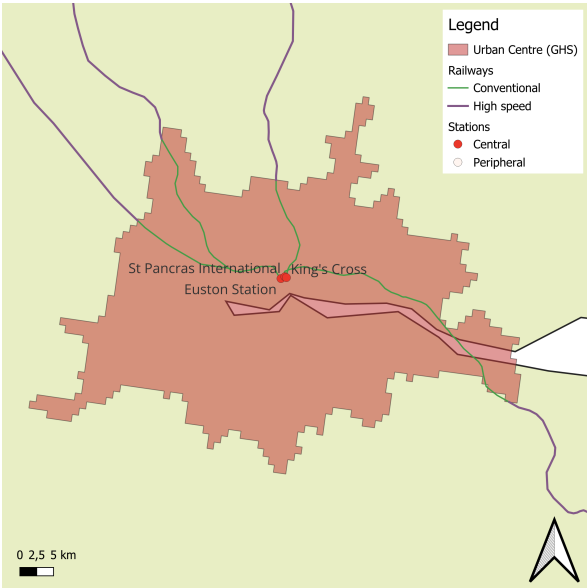


Figure D.52: Q4 Experiment 8
London base scenario

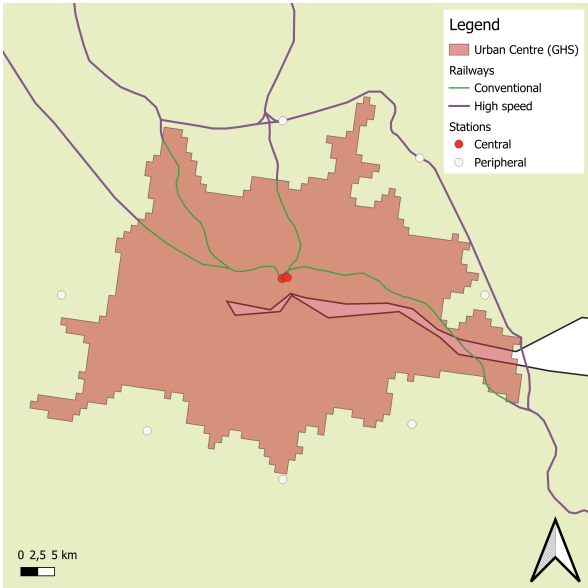


Figure D.53: Q4 Experiment 8
London station N

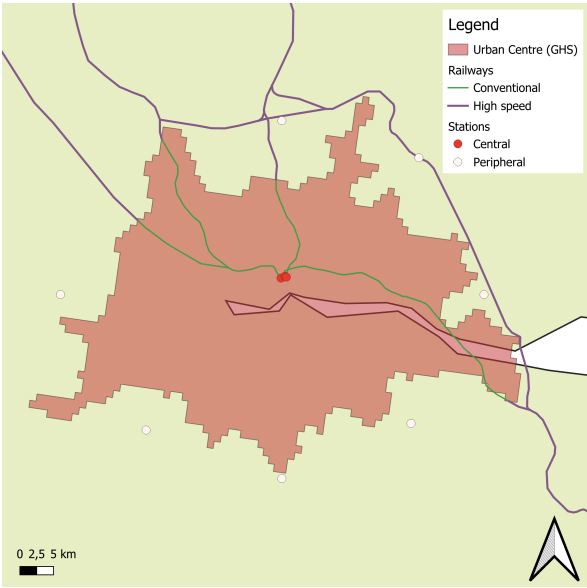


Figure D.54: Q4 Experiment 8
London station NE

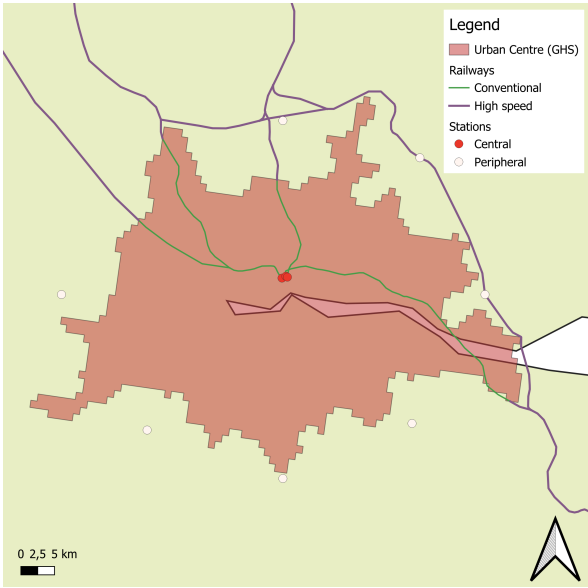


Figure D.55: Q4 Experiment 8
London station E

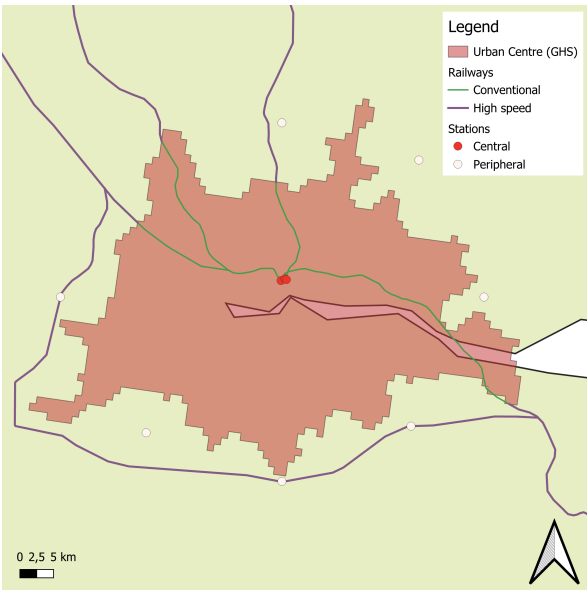


Figure D.56: Q4 Experiment 8
London station SE

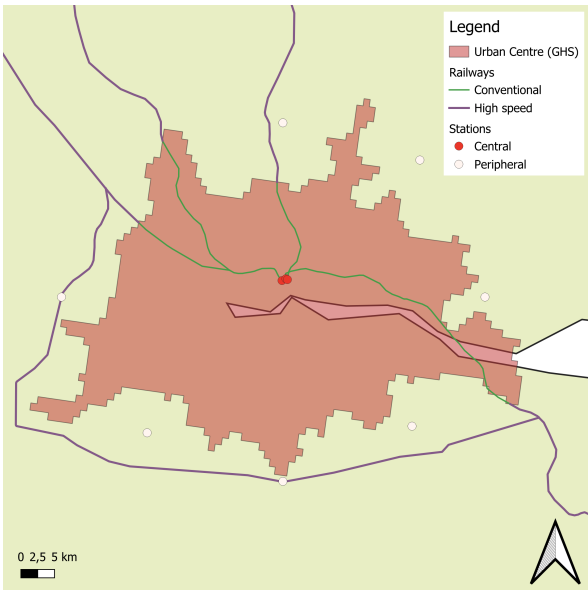


Figure D.57: Q4 Experiment 8
London station S and station W scenario

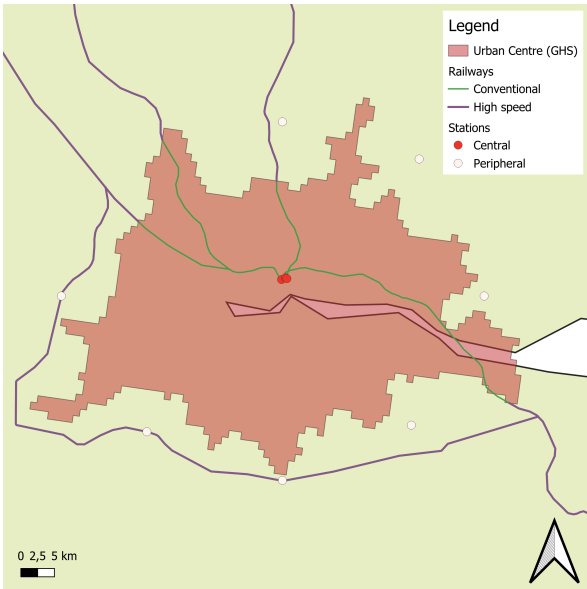


Figure D.58: Q4 Experiment 8
London station SW

D.4.9. Mannheim

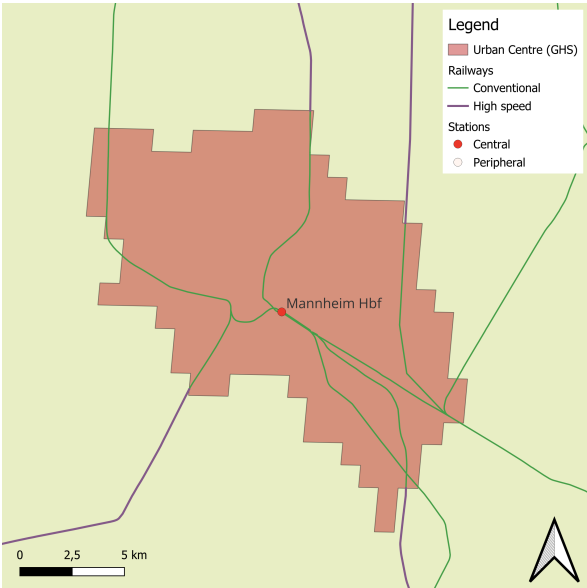


Figure D.59: Q4 Experiment 9
Mannheim base scenario

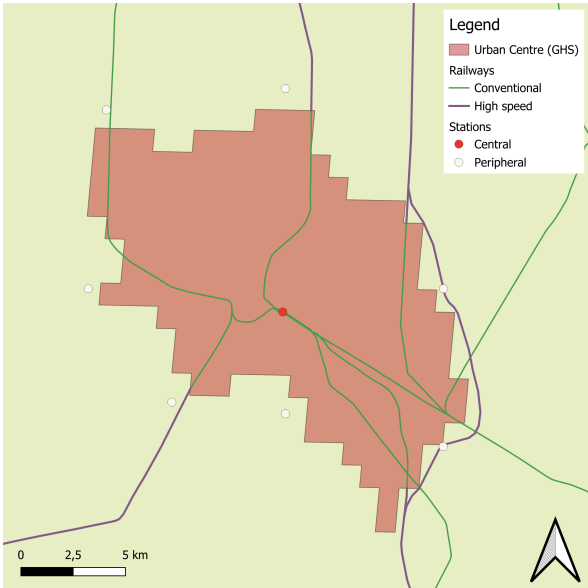


Figure D.60: Q4 Experiment 9
Mannheim station E and SE

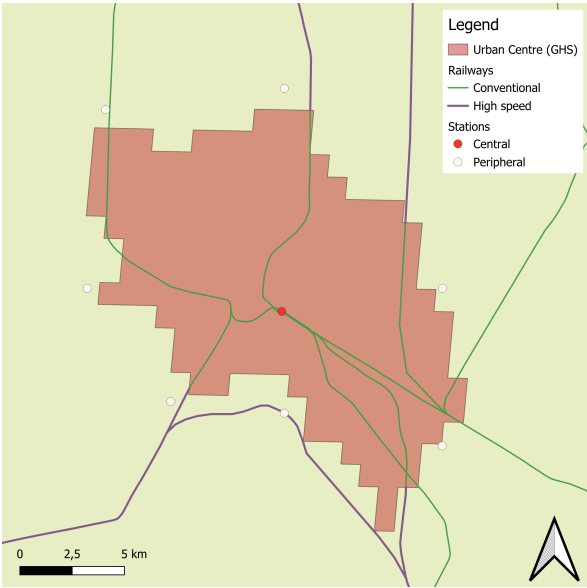


Figure D.61: Q4 Experiment 9
Mannheim station S

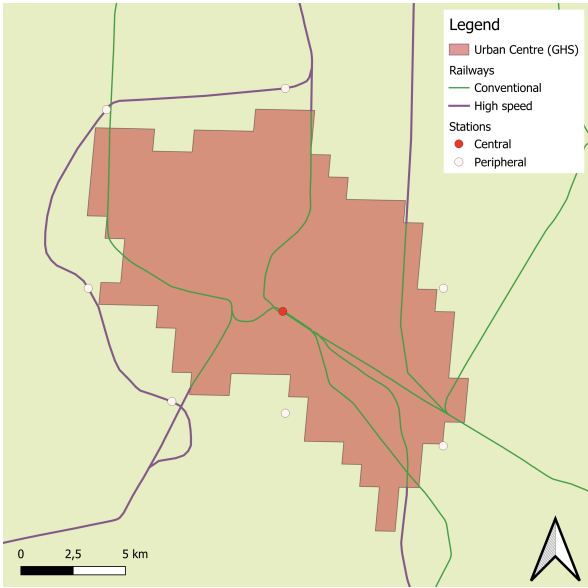


Figure D.62: Q4 Experiment 9
Mannheim stations SW, W, NW and N

D.4.10. Paris

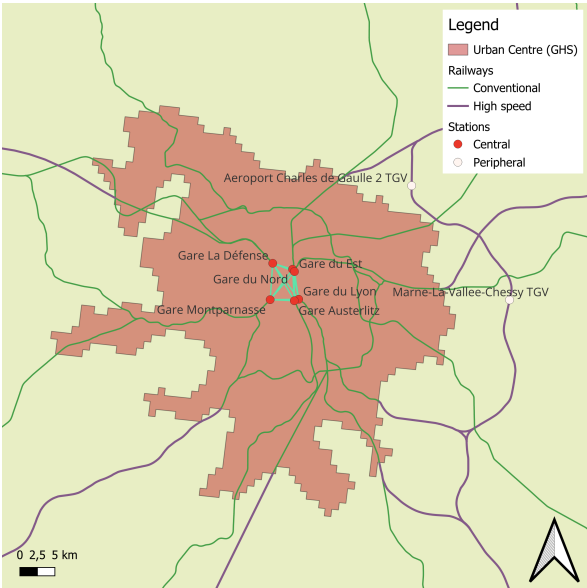


Figure D.63: Q4 Experiment 10
Paris base scenario

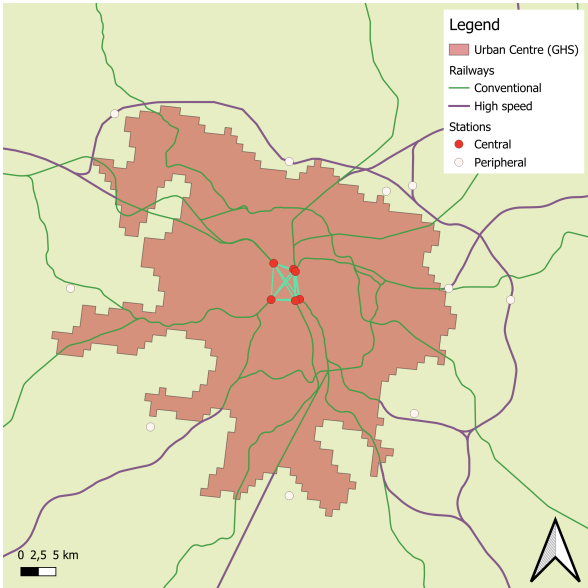


Figure D.64: Q4 Experiment 10
Paris station N

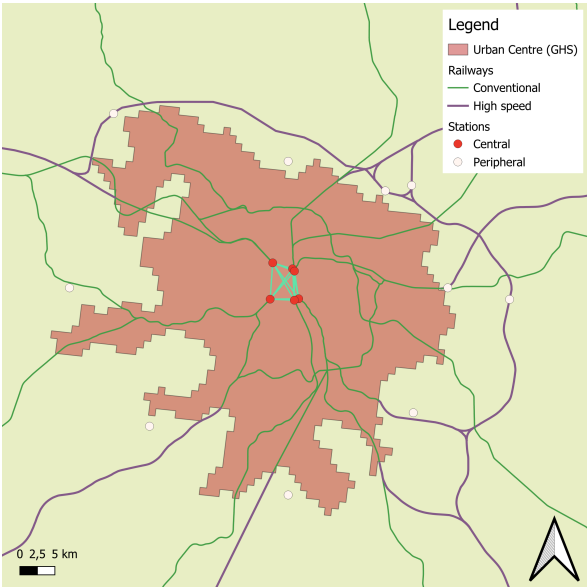


Figure D.65: Q4 Experiment 10
Paris station NE

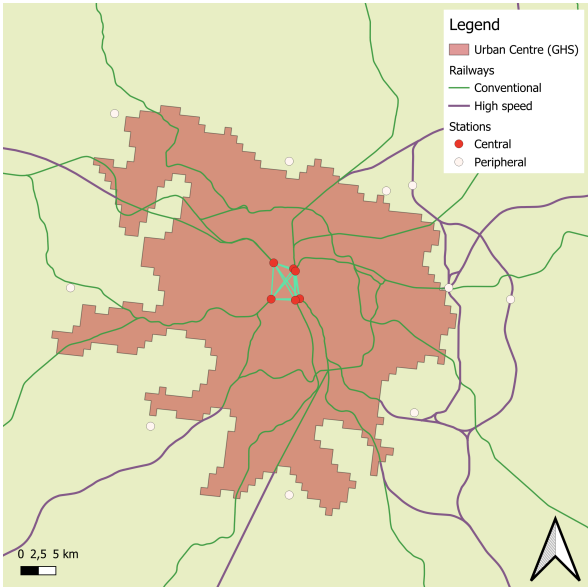


Figure D.66: Q4 Experiment 10
Paris station E

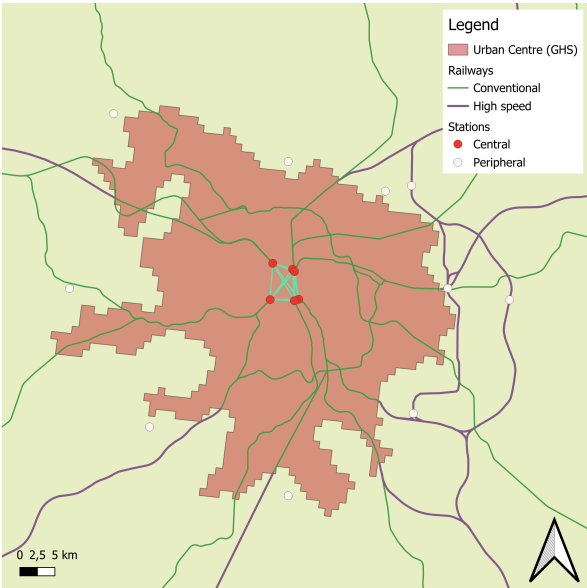


Figure D.67: Q4 Experiment 10
Paris station SE

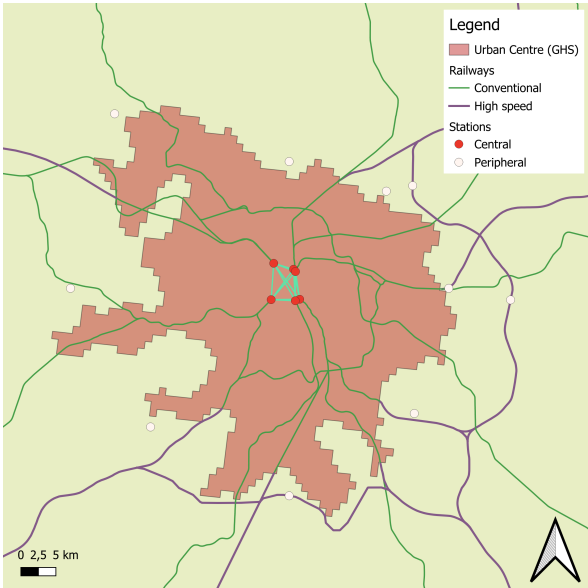


Figure D.68: Q4 Experiment 10
Paris station S

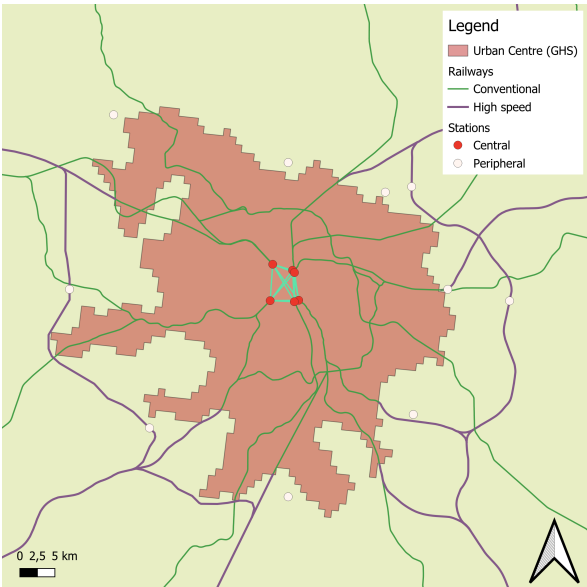


Figure D.69: Q4 Experiment 10
Paris station SW

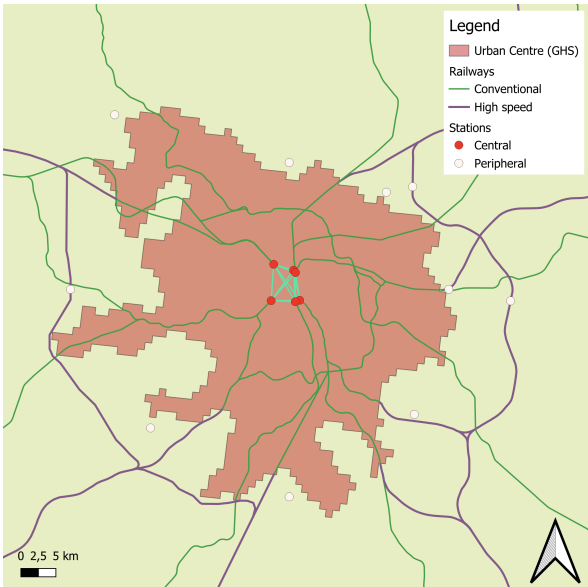


Figure D.70: Q4 Experiment 10
Paris station W

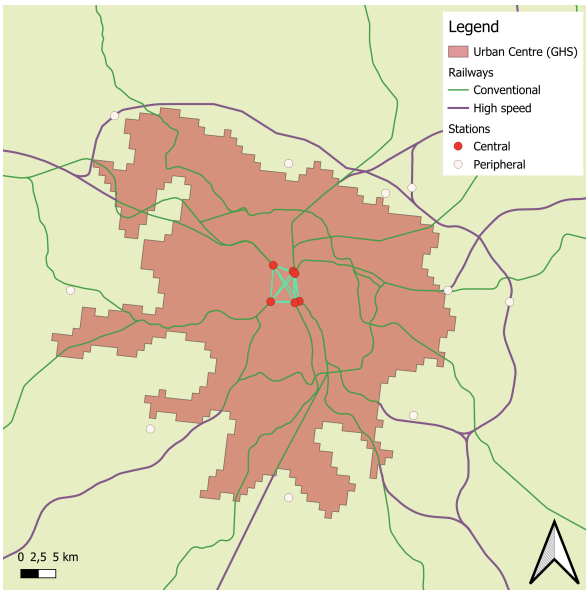


Figure D.71: Q4 Experiment 10
Paris station NW

D.4.11. Stuttgart

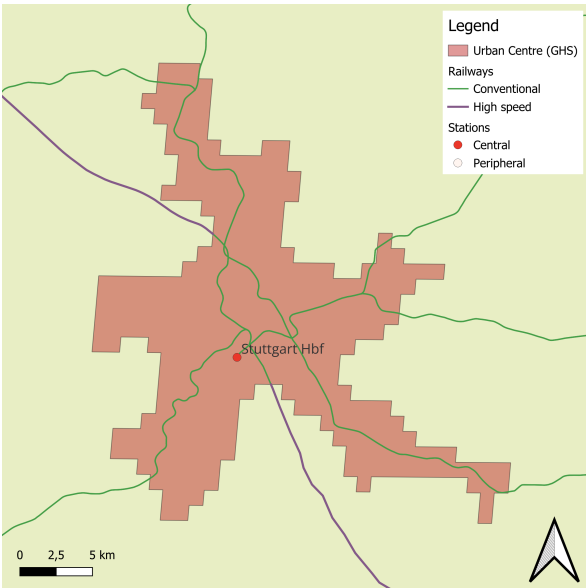


Figure D.72: Q4 Experiment 11
Stuttgart base scenario

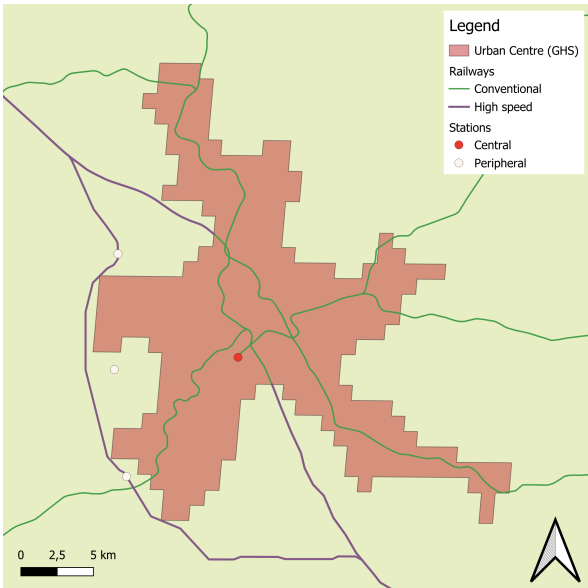


Figure D.73: Q4 Experiment 11
Stuttgart station NW

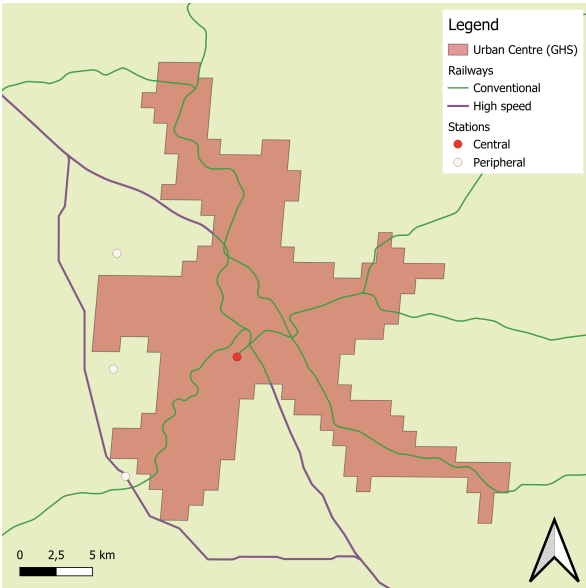


Figure D.74: Q4 Experiment 11
Stuttgart station SW

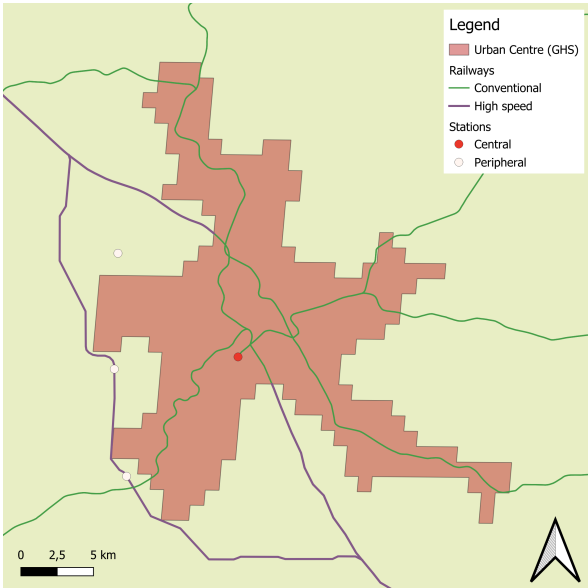


Figure D.75: Q4 Experiment 11
Stuttgart station W