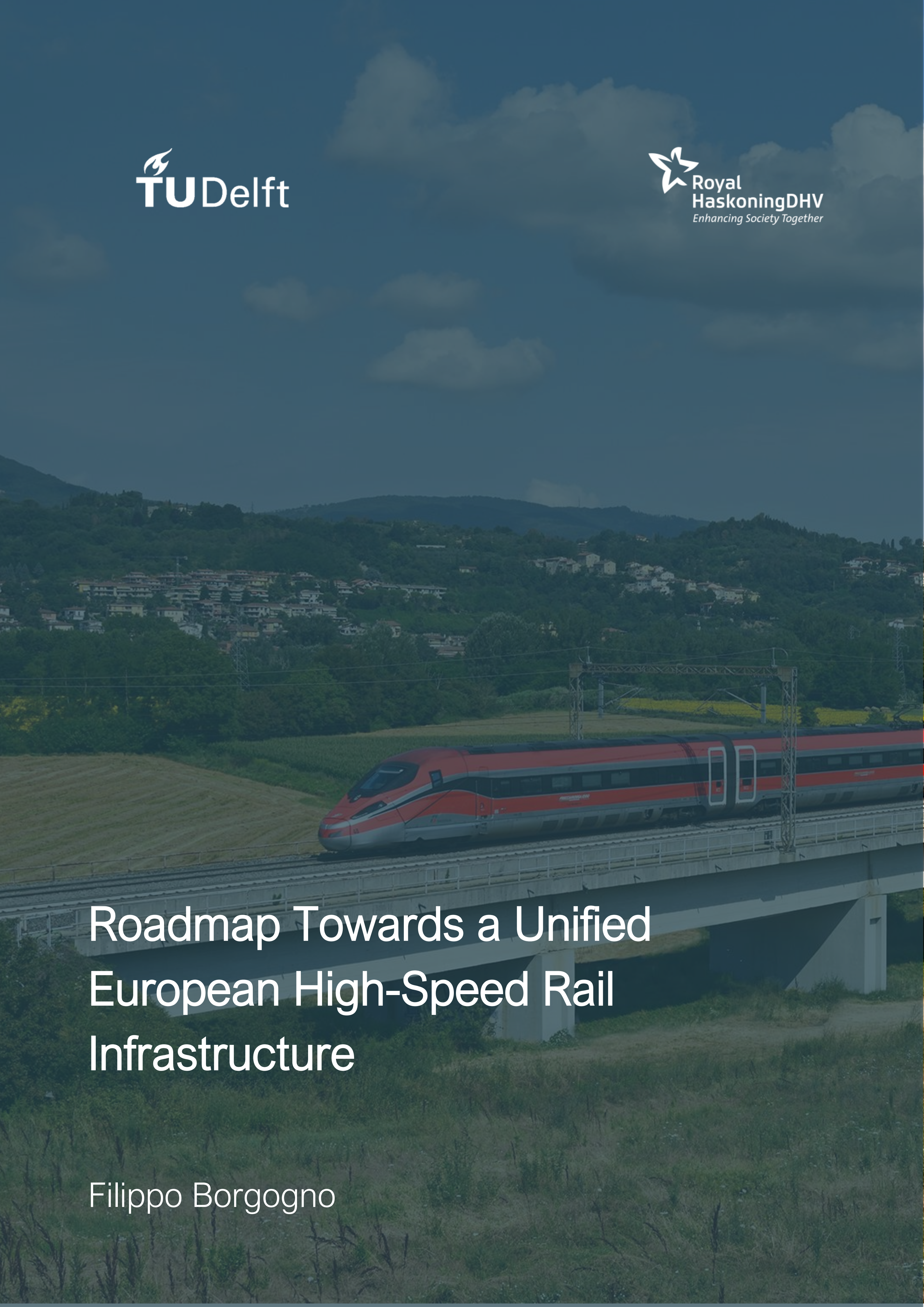


Roadmap Towards a Unified European High-Speed Rail Infrastructure

Filippo Borgogno

Roadmap Towards a Unified European High-Speed Rail Infrastructure

Author

Filippo Borgogno

Master thesis submitted to Delft University of Technology in partial fulfilment of the requirements for the degree of

Master of Science in Civil Engineering – Transport, Infrastructure & Logistics

To be defended in public on September the 11th, 2023

Graduation Committee

Chairperson	Prof. dr. Oded Cats
First Supervisor	Dr. Renzo Massobrio
Second Supervisor	Dr. Ir. Martijn Warnier
External Supervisor	Ir. Jorik Grolle

Preface

As this thesis is coming to an end, I am looking back to these three past years with emotion and incredible joy for what life can unexpectedly offer to you. This period marks my fourth time living abroad, and all in all the most difficult experience so far. Discovering a new country so close to your stereotypes yet so far, while being in the middle of a pandemic, makes you think and see your surroundings in a different way. Life is discovered at a slower pace and the little things, usually hidden, shine more than ever. The first approach with the Netherlands has been a gradual process, made of unique moments and long waiting times. After three years I feel this is a place hard to leave, a place where I understood how life can be made easy. A place where simplicity and functionality rule over the extremes, a place where speed is futuristic. In the Netherlands I learned a lot, about myself, about the opportunities of this world and I am grateful to this country that asked much from me but gave back even more. TU Delft has been a big part of it, where my passion for trains has become more stronger than ever, but now I have tools to make it a reality. Nevertheless, nothing would have happened without the people I met.

Firstly, I would like to thank my committee for believing and pushing me to improve constantly. Thank you, Oded, for accepting my proposal during challenging time, for always being there when needed, for providing critical thoughts and a nice atmosphere to work with enthusiasm. Thank you, Martijn, for the great support and opinion exchanges, for your suggestions and for your encouragements. Thank you, Renzo, for your brilliant ideas, for making me reason about things and for pushing me to never let go. Finally, thank you Jorik, your help has been really needed, thanks for making me understand the industry needs, for the insights, for the enthusiasm and for introducing me to your incredibly knowledgeable colleagues.

In this regard, a big thanks also to Royal Haskoning, that sponsored this thesis and allowed me to explore this topic even further. Specifically, thank you Barth, your support has been always good to have, thanks for your sharp questions, for the valuable suggestions and for showing me your incredibly interesting work. Thanks also to the very friendly colleagues I had the pleasure to briefly meet, who made me feel at home.

I want to extend my heartfelt thanks to my friends who have been an essential part of my life during my time in the Netherlands. Nick, Jeronimo, and Francesco, you've been there from the very beginning, and I couldn't have asked for better companions on this Dutch adventure. To Marc, you helped and supported me in every situation, and I'm proud to be your friend. Thanks to Carlos, Alex, and Edoardo, for surviving together the Covid times, and always finding some ways to have good time. Thanks to Lateesha, Zeina, Ilan, Guille, and Ernesto, you've become like family to me, and always will be. To Alessandro and Sebastiano, you've taught me the true meaning of hard work and quality. To my friends in Italy – Francesco, Alessandro, Mario, Pierre, Indre, Alberto, Emma, Giulia, Martino, and Marta – thank you for being part of this incredible journey. To my school friends – Guido, Alberto, Matteo, Davide, Kemal, Alessandro, Paolo, Sebastiano, Lisa – you continue to be a special part of my life. To Valeria for being at my side. And to everyone else, thank you for making these past three years a great memory.

Finally, thanks to my family, this thesis is for you and has been made possible by you. Thanks to my grandparents for having fought difficulties and hardships without ever loosing the values of hard work and dignity. Thanks to my grandmother, that still nowadays teaches me to be rational and to listen. Thanks to my brother, who is a great support and that I can trust until the end. Thanks to my parents, the opportunity that you gave us is something special, I promise to make the best out of it. Thanks for your hard work, for your wisdom and for never surrendering. As this thesis marks the end of a chapter in my life and the journey continues, I hope one day there will be the opportunity to bring back home, in Italy, the best things I have learned here. My passion for trains will remain a guiding force, whether as a profession or a dreamer, and with the skills and insights I've acquired, I now possess the tools to make this passion a reality.

Filippo Borgogno, Delft, September 2023.

Table of Contents

List of Figures

List of Tables

01

Introduction

Florence to Rome 'Direttissima' line inaugurated in 1977
Italy

1 Introduction

In recent years there has been an increase in societal and political attention towards rail, considered among the safest, smartest, and most sustainable transport mode for both passengers and freight. This is especially true in Europe, where its century long relationship with rail, in decline since the end of the 20th century, is being revitalized by the commitment of the European Union to create a single European Railway Area. Despite the legislative and economical efforts, rail's share remains low, especially for cross-border connections, due to lower performance and flexibility compared to other modes. In this sense, high-speed rail (HSR) presents an opportunity to address these challenges, offering speed, accessibility, and sustainability advantages. However, a unified European HSR network is yet to be realized due to poor cross-country coordination issues and policy limitations. Industry leaders and policymakers are uniting to explore the creation of a comprehensive HSR network to meet ambitious targets. This thesis delves into this topic by developing an iterative network growth model to analyse the evolution, investment strategies, and implications of a European HSR network. The aim is to enhance understanding and provide insights for stakeholders on what could be the potential long-term sequential investment strategy to achieve a connected and sustainable HSR infrastructure. In Section 1.1 the context is presented, in Section 1.2 the stakeholders are identified, in Section 1.3 the research gap is formulated, while in Section 1.4 and 1.5 the research aim and the research question are presented respectively. Finally, Section 1.6 provides the outline for this work.

1.1 Research Context

1.1.1 The European HSR Infrastructure

The first high-speed rail line in Europe with a commercial speed up to 300 km/h opened in France in 1981, between Paris and Lyon, and marked the beginning of the TGV network creation. Other European countries followed shortly after, investing in their own high-speed rail networks, and building dedicated high-speed rail infrastructure. Italy's first high-speed rail line, the Direttissima, opened in 1978, connecting Rome and Florence. Germany's ICE network began operations in 1991, and Spain's AVE network opened in 1992. The Eurostar service linking the UK with mainland Europe began operating through the Channel Tunnel in 1994. Over the years the overall European network experienced a tenfold expansion, from its 1000km in 1990 to the current 9000 km of 2017 (European Court of Auditors et al., 2018).

Not only infrastructure, but high-speed rail technology also continued to improve as well, with trains capable of faster speeds and more efficient operations. In 2007, the French AGV (Automotrice à grande vitesse) train set a new world speed record for a train on conventional rails, reaching a speed of 574.8 km/h.

Generally, demand for high-speed rail in Europe has grown in all countries where new infrastructure has been constructed. It is estimated that the introduction of HSR leads on average to a doubling of rail modal share, by replacing cars on short-medium distances and planes potentially over connections within 1000 km (Finger et al., 2022). Figure 1 shows how high-speed trains retain a dominant position for travel times up to 3 hours and a half in Europe, equivalent to distances of 600/700 km.

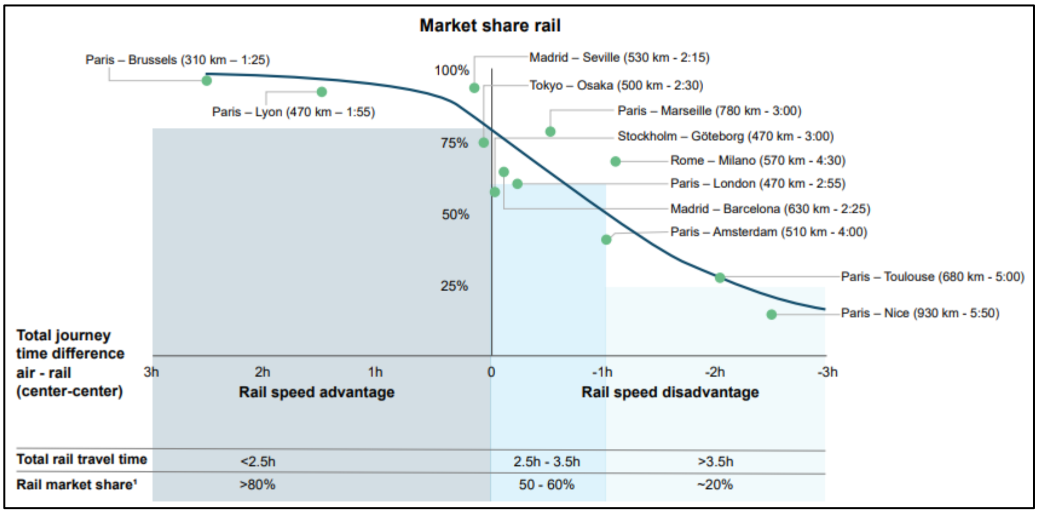


Figure 1 - Market share based on travel time differences of HSR vs air travel (UIC et al., 2022)

1.1.2 2030 and 2050 European High-Speed Rail Expansion Objectives

In line with the success obtained on the opened high-speed rail lines, and together with the vision of creating a unified network, the European Union is setting ambitious goals to further develop its HSR coverage and reach more passenger demand. Table 1 provides a summary of the current strategies, which include the European White Paper (European Commission, 2011), the TEN-T policies (European Commission, 2013) and the Sustainable and Smart Mobility Strategy of the European Union (European Commission, 2020a).

Furthermore, the recently adopted European Green Deal policy package also addresses high-speed lines, outlining the expansion potentials on many underperforming links resulting in huge environmental benefits (European Union, Agency for Railways, 2020). Note that only some TEN-T corridors include HSR infrastructure and are generally designed for 160 km/h speeds (European Commission, 2013).

All these policies and agendas ambitiously aim at increasing the competitiveness of HSR and of the rail transport in general, by eliminating barriers, increasing efficiency, and enhancing interoperability among the different national networks. The European Union aims to double the existing HSR infrastructure (9000 km) in 2030 and triple it in 2050.

Table 1 - European HSR policy formulations and targets

Plan	Objectives to 2030	Objectives to 2050
Transport white paper 2011 *(European Commission, White Paper, 2011)*	• Triple length of HSR network	• Complete European HSR network
TEN-T network strategy *(European Commission, 2013)*	• Completing Core network	• Completing Comprehensive network
Sustainable and Smart Mobility Strategy *(European Commission, Sustainable and Smart Mobility Strategy, 2020)*	• Doubling of HSR traffic (compared to 2015)	• Tripling HSR traffic • 90% emission reduction

1.1.3 Stakeholders

To better understand the current scenario and issues, it is helpful to identify the key stakeholders involved in the making of a unified European HSR network.

I European Policy and Decision Makers

The political entities responsible for the planning and the investment decision making processes of rail infrastructures, can be divided between the national and the European level.

As already introduced, the former often prioritize and influence the development of the high-speed rail infrastructures within their own country, and seldomly consider the bigger European picture and cross-border connections. Other times, a good political and legislative environment improves the utilisation and added value of high-speed rail infrastructures, as it happened with liberalisation in Italy (Bacares et al., 2019). In conclusion, the influence of national politicians and decision makers can vary among countries and can have very different effects.

The European policy makers instead, have initiated a decade long centralization process to expand the decision-making influence of the European Union over critical sectors as the rail infrastructure. Through the promulgation of the four rail policy packages and the creation of a European Rail Agency (ERA, 2023), much has been done to standardise network specifications and bureaucratic procedures (European Commission, 2013). The same can not be said when it comes to infrastructural planning and construction. In this case, the European Union can provide limited support for funding and for guidance, but its up to the single countries to manage the investment allocation and the construction process. Therefore, as mentioned in the previous Section, the European Union has not the right tools and roles yet to centrally manage a proper European-wide network expansion (European Court of Auditors, 2018). This has a profound influence on the rate of expansion and on the total added benefits that infrastructures have the potential to bring for the Community.

II European Rail Industry Leaders

In recent years, thanks also to the liberalisation of the rail sector and the progressive centralization of decision-making bodies, more rail influence groups have been created and their importance is growing. A great example can be ALLRAIL, established in 2017 with the goal to promote fair competition and rail market opening, but also other influence groups such as UNIFE, CER, RailNetEurope, and EIM. These associations are trying to promote the vision of different players in the rail market within key political decision-making centres. Not only they are asking for more standardisation, second hand rollingstock markets and increased liberalisation. Recently they have been stressing out also the need for more high-speed rail, not in single countries, but in the whole Union.

Secondly, despite rail is a capital-intensive market, there are many private companies seeking business opportunities on the newly liberalised tracks. Flixtrain, NTV (Nuovo Trasporto Viaggiatori), European Sleeper, but also digital companies like Trainline, are all pushing and waiting to see how the announced rail boost will be set on tracks.

For these actors, it is important to understand the future trends and the market evolution, to be prepared for future demand and regulations. From train manufacturers to construction companies, from consultancies to second hand rolling stock organisations, aligning the value chains in advance to the constantly evolving rail business means maintain a competitive market position.

III Scientific Community

The scientific community is deeply interested in analysing the potential of a European HSR network due to its multiple implications. Such an analysis offers an opportunity to study complex interactions between transport demand, network growth, policy decisions, and environmental sustainability. Understanding how a unified European HSR network could evolve and impact various aspects of transportation, including connectivity, accessibility, economic development, and environmental benefits, provides valuable insights for urban planning, policy formulation, and infrastructure investment strategies. Additionally, this research contributes to advancing transport network modelling techniques, allowing researchers to develop innovative approaches for addressing real-world challenges in sustainable and efficient mobility solutions across a continental scale.

1.2 Problem Definition

Despite the commitment of the European Union to achieve a common high-speed network, reality is far behind the expected results. The European Court of Auditors concluded that the plan to triple the length of the high-speed rail network by 2030 is unlikely to be achieved (European Court of Auditors et al., 2018). If in the last 30 years the network expanded to 9000 km (2017), this means that additional 21000 km of lines need to be built in just 13 years. Furthermore, data shows that the modal shift is not happening, with rail market shares still very low and only 7% of total rail traffic being cross-border (Finger et al., 2022). Currently, there is no evidence nor commitment to invest in a network of this scale. It can therefore also be concluded that, if current coordination and investment trends are not going to change, also the 2050 objectives are also likely not to be met.

The causes behind this ineffective European-wide HSR infrastructural development could be attributed to the freedom of member states to decide autonomously if, when and where to build high-speed rail infrastructure. The European Institutions are missing legal powers and operational means to coordinate the timely completion of infrastructure and have the only authority to coordinate policy actions and partially fund projects of interest. As established by the European Court of Auditors (European Court of Auditors et al., 2018) this has resulted in:

- **Poor coordination** among countries in the construction of cross-border connections, resulting in poor planning and inefficient implementation. An example is the currently under construction Turin (Italy) to Lyon (France) high-speed rail line.
- **Cost overruns** and **delays**. An example is the Stuttgart21 project in Germany currently under construction with 6 years of delay and a budget overrun of 228% (Steininger et al., 2021).
- **Low quality assessment** of real needs for infrastructural projects in the member states. Proper cost-benefit analyses are often missing, and financial management is not consistently applied in most of the investments. Alternative solutions of upgrading existing conventional lines are rarely considered.
- **Political judgments** behind infrastructural investment decisions, which consider a national appraisal scope rather than the bigger European picture (Witlox et al., 2022; Branković, 2021).
- **Patchwork of poorly connected isolated networks**, with cross-border connections neglected and not among national priorities.
- **Missing long-term strategy** towards the creation of a European high-speed rail network.

Although something is changing in this regard, as the Commission started using legally binding implementing decisions in 2018, reality is far from the desired decision-making process. The conclusions drawn by the European Court of Auditors highlight how a lack of coordination and cooperation reduces the potential of shared European projects, and significantly slows down the creation of a European high-speed rail network. Not only the European Commission is lacking the proper tools to coordinate and control HSR infrastructural development, but a missing common and shared expansion strategy is equally preventing the planning and the construction of such a network.

1.3 General Gap

The problem defined in Section 1.2 features both a scientific and a practical side, the former referring to the academic dimension of the problem and the latter relating to the more practical implications from the perspective of European policymaking and governance. Thus, the research gaps have been subdivided in these two categories and are summarised in the next two Sections.

1.3.1 Scientific Gap

Upon examining the quantitative scientific research on a unified European HSR network, several implications emerge. The studies reviewed, including Donners (2016), Grolle (2020), Ernst & Young (2023), and Deutsche Bahn (2023), share a common limitation: a notable lack of emphasis on the infrastructural aspects of the European HSR network. Rather, they predominantly rely on the predefined TEN-T policies established by the European Commission. This uniformity results in a failure to critically assess the feasibility of such network configurations or to delve into the actual costs and infrastructural designs required. While Ernst & Young (2023) provides an average cost per kilometre derived from the European Court of Auditors (2018), and Deutsche Bahn (2023) suggests expanding beyond the TEN-T configuration to meet European targets, neither study conducts a comprehensive and independent infrastructural analysis. Consequently, the absence of detailed infrastructural considerations stands out as a primary research gap in this domain.

Regarding the modelling framework for comprehensively mapping the dynamic evolution of high-speed rail (HSR) investments, the iterative growth formulation has been identified as the preferred option. However, a significant methodological gap is evident in the literature. Existing studies, such as Cats et al. (2020, 2021), Peters et al. (2014), and Pablo-Marti et al. (2017), primarily apply this framework to urban, metropolitan, or regional scenarios. Thus, there's a notable absence of rigorous testing on a continental scale, especially within a detailed spatial analysis framework. Bridging this gap through large-scale, spatially informed modelling represents a crucial avenue for future research in HSR network development.

1.3.2 Practical Gap

The practical gap revolves around the European HSR network case study and examines its implications for practical applications and policymaking, particularly from the perspective of European governance bodies. This gap becomes evident when we consider the absence of a clear, shared, and strategically relevant sequential long-term strategy needed to obtain the desired network configuration. This deficiency leaves the industry without a cohesive, forward-looking plan to guide their infrastructural interventions over the coming decades. Existing action policies establish fixed objectives without a strategic, step-by-step investment plan, projecting a static network configuration for specific years. Consequently, none of the studies furnishes a comprehensive year-by-year roadmap for achieving the final expansion objectives. Additionally, a static analysis falls short in capturing the dynamic factors influencing network evolution and investment allocation, particularly when addressing detailed infrastructural modelling. Consequently, the research gap canters on the absence of a comprehensive, long-term network development strategy for creating a unified European HSR network.

In conclusion, existing research reveals three critical gaps: a deficiency in comprehensive infrastructural analysis, limited testing of the iterative growth framework at a continental scale, and a lack of a clear, shared, and strategically relevant long-term strategy for European HSR network development, which has implications for policymaking and planning.

1.4 Research Aim

Given the coordination issues highlighted by the European Court of Auditors (2018), and the research gaps identified in Section 1.3, the aim of this study is therefore to address the creation of a missing long-term strategy that could lead to a unified European high-speed rail network. In detail the main research objectives can be identified as:

1. Understanding where, when, and at what cost to build high-speed rail infrastructure based on a centralized decision-making process.
2. Study the dynamic network evolution in the context of the existing HSR infrastructure
3. Understand the dynamic interaction between infrastructural expansion and the long-distance transport market
4. Improve the transparency and increase the scientific knowledge behind the centrally coordinated decision-making processes regarding the investment towards a unified European HSR network.
5. Provide a novel methodology to model the dynamic network evolution in line with the objectives.

1.5 Research questions

Closely related to the research aim, the main research question and sub-research questions can be formulated. By taking in consideration the research context and the research gap, the main research question follows:

> What is the most economically beneficial centrally designed long-term sequential investment strategy for the creation of the European high-speed rail network?

In relation to the defined research question formulated above, Table 2 provides an overview of the sub-research question defined for this thesis.

Table 2 - Sub-research questions

Question
1. Which is the sequence of high-speed rail investments that could lead to the creation of a unified European HSR network, while minimizing costs and increasing benefits?
2. What are the impacts of a potential unified European HSR network in terms of infrastructural costs, travel time utilities and externality savings?
3. How would the modal split of the European long-distance transport market be impacted by the creation of a unified European HSR network?
4. To what degree does a national or European appraisal process affect the investment sequence of high-speed rail links?

5. What are the key considerations that can be drawn from the infrastructural expansion towards the creation of a unified European HSR network?

1.6 Report Structure

The following thesis includes in Chapter 2 a literature review of the unified European HSR network and on the modelling practices to study the dynamic network evolution. Then, in Chapter 3, the methodology and model framework are detailed and explained. The developed model is then applied in a case study, presented in Chapter 4. Next, the results and limitations are discussed in Chapter 5. Finally, a conclusion is presented in Chapter 6.

02

Literature Review

Paris to Lyon LGV Sud-Est line inaugurated in 1981
France

2 Literature Review

The following chapters present a review of the literature considered for this thesis. Firstly, in Section 2.1 the definition and the context concerning the unified European HSR Network are discussed. Secondly, in Section 2.2, the quantitative studies on the topic are presents, while in Section 2.3 the network growth modelling principles and methodologies are reviewed in the context of iterative network growth models.

2.1 The Unified European HSR Network

The concept of a trans-European HSR transport network is not new and has been discussed alongside the creation and the political development of the European Union, often considered as a potential catalyst for European integration (Ross, 1994). One of the first proposal was done in 1989, aiming to address capacity limitations, increase speeds, and improve accessibility of European railways (Community of European Railways, 1989). The document recommended a masterplan for expansion, including new and upgraded lines. This has been further emphasized during the 2001 Gothenburg European Council, where more environmentally sustainable transport policies and the development of multimodal corridors and high-speed trains was discussed. The 2003 White Paper defined priority projects, with the network expected to expand to 9,693 km by 2008 and planned growth to 32,000 km by 2030. In a later stage, environmental justifications for high-speed rail further gained significant importance alongside capacity and connectivity goals (González-González et al., 2010).

In line with the early proposals, recent years have seen increased interest towards a more rail interconnected Europe, especially due to environmental concerns and the need for improved efficiency over long-distance cross-border transport. The 2011 transport white paper has set important goals for the completions of the European high-speed rail network to 2050, while tripling its length to 2030. While the latter goal seems currently unlikely to be reached (European Court of Auditors, 2018), the shift of the majority of medium-long distance passenger transport to rail within 2050 (European Commission, White Paper, 2011) could still be a feasible option.

More concrete network expansion plans have been formulated with the TEN-T core and comprehensive network strategy, which identifies Europe’s most important transport corridors and aims at improving their robustness and technical interoperability (European Commission, 2013). Although rail has an important role in the plan, high-speed connections still depend on national needs and national visions, with different types of dedicated and mixed traffic designs that can be adopted based on the situation. If on one side this allows for more flexibility, it does not contribute to the wider goal of creating a standardised European network. After the 2021 revision, the plan has not changed much regarding HSR, which still lags behind in importance to topics such as freight transport and standardisation of the current network. The key transport corridors have been identified, but a long term HSR expansion plan along them is currently still a vague hypothesis.

The 2020 Sustainable and Smart Mobility Strategy (European Commission, 2020a) revised the HSR goals of the White Paper (European Commission, 2011), which now aim at doubling the high-speed rail traffic by 2030 and tripling it by 2050. To achieve this, the Commission recommends Europe to build a high quality transport network with HSR service on short-haul distances and clean aviation services for long-haul coverage. To support these claims, the recently published report on boosting long-distance and cross-border connections (European Commission, 2020b) identified several potential improvement scenarios for a better exploitation of the rail demand. Among these 16 potential night trin OD pairs and

27 new long-distance cross-border pairs to be operated by high-speed rolling stock material. No mention has been made about specific infrastructural expansion plans.

Despite the ambitious goals of European policy makers, the actual realization of the project is slow and well behind the targets proposed. Two recent reports, one by the European court of auditors (European Court of Auditors, 2018) and one commissioned by the directorate for regional urban policy (European Commission, 2018), identified significant problems towards a European HSR integration. Poor coordination among member states, together with weak decision-making powers of the European Commission, brought to delays, cost overruns and the investment in low value add projects. This is especially true for cross-border infrastructures and investments, which have been heavily neglected (European Commission, 2018) and are in constant decline (European Commission, 2020b) with less active routes available compared to 2001 and only 7% of long-distance trips undertaken by train (European Commission, 2020b). In both reports the formulation of a more concrete long-term planning strategy is recommended, suggesting a more predominant role of European decision-making process. Furthermore, the reports also highlight the importance of adopting a cross-border approach for appraisal, overcoming the limitations imposed by national borders and standards.

Currently no progress has been made in this regard, with the only significant improvement toward a single EU rail area being the creation of the European Rail Agency and the adoption of the 4th rail package in some countries. Finger et al., (2022) still argues in 2022 that HSR is among the preferred solution for sustainable transport within 1000 km, but that national priorities still prevail over a common expansion process. For the authors, the next step is to connect the fragmented national infrastructures, or “ineffective patchwork” (European Court of Auditors, 2018), so to improve travelling times among EU’s largest cities. The potential is there given that the 1000 km threshold allows many connections to be competitive for HSR within the continent. As the continent stands at the crossroads of integration, the realization of a seamless and efficient European rail network hinges upon navigating the complex interplay between national autonomy and collaborative expansion.

2.1.1 Summary

The concept of a trans-European HSR transport network has long been discussed in the context of European integration, with milestones set to reach ambitious expansion targets by 2030 and 2050. However, the realization of a comprehensive European HSR network has faced challenges, with coordination issues, national priorities, and cross-border complexities leading to delays, cost overruns, and underinvestment in cross-border infrastructures. The European Court of Auditors and other sources highlight the need for improved cross-border strategies and more centralized decision-making processes. Despite the potential benefits and endorsement from researchers, the expansion of HSR in Europe still grapples with balancing national autonomy and collaborative network integration. As Europe seeks to establish a seamless and efficient rail network, the challenge lies in bridging the gap between national interests and collective expansion efforts. Many advocate the need for a less distributed decision making process, in favour of a more centrally coordinated governance. Currently, these issues are still a relevant discussion topic, presenting significant barriers to the development of a future potential trans-European network.

2.2 The European HSR Network in the Scientific Community

Scientific works have further studied the implications of a European high-speed rail network in terms of accessibility, innovation development, demand distribution and service provision. Gutierrez et al. (1996)

analysed the spatial distribution of railway accessibility in the European Union, identifying patterns of accessibility and the presence of corridors and islands. The introduction of high-speed trains is expected to reduce core-periphery imbalances and improve accessibility with the potential of risk increasing spatial polarization towards major urban areas. Vickerman (1997) analysed the early developments of the main national European HSR networks, highlighting the issue related to network design, alternative modes accessibility, infrastructural investment, and service quality. The review highlights challenges in studying rail development impacts deriving from infrastructural investment to drive growth, and the importance of the entire network's quality. In line with Gutiérrez at al. (1996), major impacts are expected in increased accessibility, favouring major metropolitan areas and interchange points at the expense of secondary centres. Concerns arise over divergences in accessibility between core and peripheral regions and within the core, potentially impacting economic development. The service design and the infrastructural economical considerations are still not fully studied given the early stages of HSR development.

Nash (2007) is among the first to discuss the role of high-speed rail innovation in the context of a developing European international HSR network, highlighting the national focus in the planning and construction of dedicated or mixed traffic lines, as well as the link-based appraisal approach which has ignored international routes and failed to capture overall network effects. In line with institutional reports reported in the previous Section (European Court of Auditors, 2018; European Commission, 2018; Steer et al., 2020, Finger 2020), he identifies institutional barriers and independence of national railway systems as the main problem in creating an integrated European high-speed rail (HSR) network. The author underlines that overcoming these institutional barriers is crucial for the development of a cohesive European HSR network.

The study by Donners (2016) is one of the first quantitative studies on the topic, aiming at studying the seating capacity potential of an integrated European Rail area that could go beyond the consideration of national borders. The methodology developed is based on the 4-step transport modelling approach, providing an initial modelling framework to assess the potential trip demand, trip distribution, mode choice and link line assignment for long-distance transport in Europe. The results show a potential for 240 million more trips (22% increase) compared to the current situation, with the international share of trips potentially rising from 6% to 25%, or even 37% for the growth scenario. However, the analysis revealed an insufficient level of service on existing connections, with a reduction of 40% in effectively offered seats. Approximately 58.6 million trips on international links remain unserved due to unattractive service. This study presents one of the first attempts to quantitatively model the potential of the European passenger rail market but is limited in its analysis as it does not address the service design nor the infrastructural developments within the scenarios. In relation to the latter, the study assumes that different rail network configuration per scenario based on the TEN-T infrastructural expansion plans.

The work of Grolle (2020) addresses the service design limitation of Donners' (2016) work, by studying line configurations patterns and understand the implications from both a pricing and governance perspective. The methodology applied relies on the Transit Network Design and Frequency Setting Problem (TNDFSP), for the first time applied to an HSR environment. The enhanced HSR design is obtained by analysing design variables, evaluating pricing and governance strategies, and proposing improvements. Implementing centralized governance and internalizing external costs can benefit all stakeholders simultaneously, increasing the HSR market share from 14.7% to 29.9% and improving the societal cost-benefit ratio by 20.0%. The study highlights the importance of addressing unprofitable passengers, improving cooperation, and integrating overlapping and border-crossing lines in network design. It also identifies the contradictions between national and international interests and the significance of critical infrastructural elements. As the study brings further insights in terms of network design to Donners' (2016) work, the previously identified limitations concerning infrastructural implications is still present. In fact, the considered rail network is based on the TEN-T network expansion plans and does not consider the economical implications of such investments nor alternative options.

Some interesting studies have been recently published by the rail industry leaders, further highlighting the increasing interest concerning the topic.

In March 2023 Europe's Rail Joint Undertaking (EU-RAIL) commissioned a study for the creation of a European HSR master plan connecting all major European cities, with a mix of new and upgraded lines (Ernst & Young, 2023). Benefits would yield around 750 billion euros at a present cost of 550 billion euros. The methodology applies a series of shocks in terms of future regulatory and technological developments, so to forecast demand changes. Based on the demand, a Cost-Benefit analysis is conducted to estimate the both the NPV and the BC ratio of the proposed pan European HSR network, which is based on the 2030 and 2050 TEN-T core and comprehensive network goals and expanded with additional lines. The obtained economic indicators a further tested under different growth scenarios and varying infrastructural costs. The demand shock model provides a potential realistic modelling option to study future developments in the field. At the same time the formulation of the potential network connections and infrastructural costs seems rather vague, especially when country specific parameters are not considered. Furthermore, the report does not indicate where to begin and which is the preferred sequence to reach such goals. Nevertheless, this work can be considered as one of the closest studies to what is aimed with this thesis in terms of appraisal practice.

The most recent paper on the topic so far has been commissioned to PTV Group by Deutsche Bahn, in collaboration with the major European rail undertakings. The study explores the potential topological network configuration of a metropolitan European HSR network, which could improve cross-border accessibility and reach EU's HSR traffic goals. For this purpose, a travel demand model has been developed to predict the growth of transport demand due to population changes, prosperity changes and travel time improvements. The latter infrastructural improvements are based on existing expansion plans related to the TEN-T corridor characteristics. To compare the obtained demand changes, the 2030 and 2050 goals of doubling and tripling HSR traffic based on EU policy targets are taken as a benchmark. The results shows that the current infrastructural expansion actions are not enough to meet EU targets, and that only a proper metropolitan network, consisting in an additional 21000 km of new lines, would allow to reach such levels by 2050. Similarly to previous works, the demand assessment is conducted in more depth than the actual infrastructural expansion options, which rely on the TEN-T corridor assuming

Other studies have focused on more specific geographical areas or topics. Holzner et al. (2018) studied the potential developments of a European Silk road, two major transport corridors of 11000 km comprising different modes to connect western and eastern Europe, including Russia and the Balkans. This would increase economic growth by 3.5% at a cost of 1 billion euros. While the corridor choice is based on the authors own judgement, some interesting methodologies are formulated for assessing the infrastructural potential of a country and the investment costs of new infrastructure. For the former, a regression based on GDP per capita, population density, and terrain conditions highlights the negative residual value of each country compared to the European average, identifying improvement areas. For the latter, the Austrian HSR costs have been adapted to other countries based on the price level index.

The overall final economical impact is measured with the IMS's methodology to evaluate macroeconomic effects of public investment on the real economy. Despite the preliminary economic feasibility of the proposed investments provides interesting points of reference, there is a significant lack of scientific considerations behind the choice of the corridors.

The same applies also to Creel et al., (2020), who propose our major Ultra Rapid Train lines connecting all major cities of Europe and the western Balkans, running preferably on dedicated infrastructure with speeds up to 350 km/h. The final network would total 16600 km of new lines at a cost estimated to be around 1.1 billion euros, amounting to 7.5% of the participating countries' GDP. The main methodological approach is based on Holzner et al. (2018). Finally, both works are linked by the same interesting proposition to allocate all the resources to a public limited company owned by the countries involved, which follows the recommendation of institutional European bodies as previously seen (European Court of Auditors, 2018).

The last papers revied are by the United Nations Economic Commission for Europe (UNECE, 2017; UNECE, 2021), which studied the potential of a Trans-European Railway network to serve as a high-speed transport backbone to connect the major eastern urban regions with western Europe. In the latest report, phase 2 (UNECE, 2021), HSR corridors are firstly identified based on a set of international criteria, missing links and bottlenecks are analysed, and finally a CBA analysis is performed to assess the impact of such network development. Interesting points of this study are the emphasis to adopt a corridor approach for benefit and efficiency maximisation. Furthermore, the study provides useful data to assess infrastructural cost values for surface and underground infrastructure, based on elaborations by UIC. This study is also the only one that clearly identifies a schedule for investments, although deadlines are set in a similar way to EU goals.

2.2.1 Summary

In conclusion, studies concerning the quantitative analysis of a trans-European HSR network a quite limited in number but are gaining increased interest from both the scientific and the rail industry community. This follows the formulation of European policies which have set important goals for 2030 and 2050. The final considerations to be drawn are mainly three. Firstly, most of the studies consider the current TEN-T network policies as base networks for their studies, without questioning their actual feasibility. Secondly, all studies focus on obtaining a final static infrastructural network overview, rather than studying the step by step process to reach such final state. Lastly, studies have focused on demand assessment (Donners, 2016) economic feasibility of proposed investments (Ernst & Young, 2023; Deutsche Bahn et al., 2023) and the potential design of HSR lines and frequencies (Grolle, 2020). Less attention has therefore been given towards sequential infrastructural modelling and the role of geographical space within cost structures and network development. Table 3 summarises the scientific works reviewed regarding the topic.

Table 3 - European HSR quantitative studies summary

Reference	Objective	Case Study	Main Methodologies	HSR Infrastructure
Donners, 2016	Provide travel & seating capacity of European passenger market	European Union, major urban centres in bordering countries	Market assessment: 4step transport modelling	Based on TEN-T and current network
Holzner, 2018	Assess economic benefits of two new 'European Silk Road' transport corridors	European Union, Balkans, Russia	Infrastructure improvement index. Cost estimation: Reference value and country specific price levels.	Own elaboration of the Author

Creel, 2018	Assess economic benefits of four ‘Ultra Rapid Train’ transport corridors	European Union, Balkans, Russia	Based on Holzner et al. (2018). Centrally coordinated investment fund.	Own elaboration of the Author
Grolle, 2020	HSR line configuration and impact assessment	European Union, major urban centres in bordering countries	Market assessment: 4-step transport modelling Service and impact assessment: TFSNDP optimization	Based on TEN-T and current network
UNECE, 2021	TER state HSR network impact assessment	TER member states	Growth model, corridor approach Impact assessment: CBA	Based on existing, TEN-T and potential connections
Ernst & Young, 2023	Pan Eruopean HSR network impact assessment	European Union,	Market assessment: Demand shock model. Impact assessment: CBA	Pan European HSR network: TEN-T network plus additional links
Deutsche Bahn & PTV Group, 2023	Simulate the effect on the achievability of EU’s 2030 and 2050 targets	European Union	Transport demand Model, Network identification Impact assessment: CBA	Metropolitan Network based on TEN-T and own elaborations

2.3 Modelling the Growth of Transportation Networks

The evolution process of transportation networks refers to the dynamic changes that occur in transport infrastructure, connections, and spatial patterns over time in response to various socio-economic, technological, and environmental factors. Changes entail the expansion, modification, and reconfiguration of transportation systems, and involve the shifts in network topology, connectivity, accessibility, and modal choices, reflecting the changing needs and demands of societies. This process is influenced by factors such as population growth, urbanization, technological advancements, economic activities, land-use patterns, policy interventions, and sustainability considerations.

Literature recognizes that network growth of public transport network growth is the outcome of a sequence of inter-dependent investment decisions based on the dynamic interactions between travel demand and service provision (Cats et al., 2021), as well as on competition between the attraction potential of urban hubs and geographical constraints (Yan, 2009). Sui (2012) argues that public transport patterns primarily depend on spatial traffic distribution, passengers demand, and expected utility of investors within the transport network. Worth to mention is the work by Barabasi et al. (1999), which introduces the concept of preferential attachment. The authors suggested that many real networks exhibit preferential connectivity during their evolution process, where a node with a higher weight (e.g., Population, economical activity, demand potential) has a higher probability to be connected with a new node in a network.

Understanding the evolution of transport networks is essential for effective infrastructure planning and transportation management, as it helps anticipate future demands, optimize network efficiency, and promote sustainable and equitable mobility solutions. Scientific studies have proposed different strategies to quantitatively model the evolution of transport networks. Xie et al. (2007a) presented an extensive literature review about the progress that has been made over the last half-century in modelling and analysing the growth of transportation networks, pointing out the challenges that are faced to model the complex process of transport development. The studies have been categorized following five main streams: transport geography, optimisation and network design, transport network growth models, economics of network growth and network science.

Contrary to optimization models, which aim to identify the most efficient or optimal configuration of the network based on predefined criteria, transport network growth models focus on understanding the underlying processes and dynamics that drive the development and evolution of transportation networks over time. They provide insights into the complex interactions between transport demand, spatial structure constraints, policy interventions, and the transport infrastructure developments. The iterative feedback process of these models allows therefore analysing and explaining the dynamical growth and adaptation to changing circumstances. Additionally, these models can help identify emergent properties and predict future network configurations, supporting long-term planning and policy-making decisions. Therefore, given the aim of this thesis, iterative transport network growth models, coupled with concepts of transport geography and network science, will be analysed, and reviewed.

Concerning transport network growth models, early approaches can be found in the work of Black (1971) and Levinson et al. (2005). The former formulated a link location model to simulate a diffusion-oriented network growth. At each time step, the model is allowed to perform an investment based on how much profit it generated from transport in relation to its investment costs. Additionally, the cosine of the angle formed by the addition of a new link to an existing link of the network avoids backtracking or the creation of small angles. Although the model demonstrated to be quite accurate in reproducing Maine's rail network, it is limited due to its tree shaped oriented evolution structure, which is unsuitable to realistically reproduce unknow network structures. The latter modelled a regular road network web to assess the emergence of road hierarchies. Through an iterative process of speed improvements based on the revenue generated by traffic, the authors showed the emergence of different network structures strictly dependent on the initial spatial demand distribution of the underlying network. Although this paper addresses the upgrading of an existing network rather than its expansion, it highlights the modelling potential of iterative investment decisions in describing the relationship between network evolution and demand distribution. Both papers make use of decentralized investment allocation rules, which perform local optima choices for either link construction or link upgrading.

Xie et al. (2007b) further proposes a modelling approach simulating the iterative evolution of land transport networks based on the interaction, investment, and disinvestment process of interurban roads. The model outcomes highlight the spontaneous organization of network hierarchies in the variable network, demonstrating the importance interaction between demand and transport structure in the topological evolution.

Peters et al. (2014) propose a methodology for analysing system-wide modal ridership and assessing the potential for high-speed rail (HSR) as a part of the existing multimodal transportation system in terms of ridership. The study models the interaction between demand and supply within an iterative modelling framework called LUCIM (Long-term User and Community Impact Model), which includes dynamic parameters such as energy market, demographics, technological adoption, economy, ridership distribution and impact assessment. The experimental setup and results show the importance to include long-term user and community impacts in the assessment step, as well as the relevant potential of HSR in the Midwest region (USA). This work provides interesting inspiration in terms of how to model macroscopic interaction between infrastructure investment and the community environment of a specific region. Nevertheless, topological network configuration is fixed and based on existing plans, limiting the model's ability to really obtain the optimal solutions from the aforementioned trade-offs.

Pablo-Marti et al., (2017) studied how the spatial distribution of towns affects existing transport network designs, by further analysing the decision process leading to the choice of which connections to improve first. The model they proposed presents an interesting iterative formulation, where at each iteration all cities express their improvement choice based on the minimum spanning three towards other hubs obtained with the Dijkstra algorithm. Then the central decision maker accounts for these preferences, assuming either that all cities have the same voting power, or that the latter is proportional to population size. Finally, an investment decision is made, upon which future iteration will rely on due to path dependency. The results show different network evolutions influenced by initial network states, with progressively diminishing benefits strictly related to population and improvement potential of the links. The authors strongly support the use of decentralized iterative design processes to achieve realism and efficiency, as opposed to global optimization. In conclusion, this study proposes a first decentralized design methodology that analyses network evolution without considering any base network, solely based on the dynamical interaction between the parameters considered and the topographical distribution of cities. The methodology has great development potential and is considered as reference for the initial modelling of this study.

Finally, Casts addresses the iterative network growth topic with two studies. In the first one (Cats et al., 2020), an iterative cost-benefit analysis evaluates candidate investment for different transport modes, by weighing travel time savings against infrastructural costs. The model is applied to a monocentric urban public transport network and tested under different population distribution decay functions. Results show different network evolution dynamics, with an early expansion phase followed by link intensification and finally densification of the core. This suggests the strong relationship between population distribution and network topology. Limitations can be mainly seen in assuming a monocentric urban structure and by analysing each transport mode independently. To improve on the latter considerations, the second study (Cats et al., 2020) focuses on the evolution of transport networks in polycentric urban regions with multi-modal network structures. Still based on the 4-step demand modelling, the iterative investment model developed invests in the best scoring candidates from a Benefit-Cost ratio (BCR) perspective. Furthermore, three types of investments can be carried out between expansion, densification and increasing frequencies. Candidate investments must always be attached to the existing network in line with preferential attachment principles. Finally, network configurations are obtained for four polycentric configurations: London, Tokyo, the Flemish Diamond and the Rhine-Ruhr area.

The study once again remarks the strong relationship between population distribution and network configuration, showing that more uneven population distributions result in the construction of fewer links and consequently a less connected and shorter network. The network evolution is characterised by an initial expansion phase, followed by an alternation between bulking and densifications, somehow similarly to the monocentric urban study. Furthermore, path dependency and the need for investments with negative returns are highlighted. What the study is missing is an analysis of infrastructural costs that considers spatial factors and is limited by imposing new links to be connected to the existing network.

2.3.1 Summary

Concerning the modelling of the growth of transportation networks, literature highlights the potential of using a feedback process to understand the dynamic interaction between the network evolution and the factors affecting it. These being mainly the population distribution, the spatial configuration, the network expansion costs as well as the characteristics of the transport modes considered. Most of the models found in the literature focus on the growth of public transport network in urban contexts, as well as modelling the growth of road networks. Only one study includes high-speed rail, but it focusses lies mainly on highlighting the societal benefits for rural communities giving existing infrastructural plans. There is a general lack of models focusing on network evolution on bigger scales, as well as network evolution based on a real-world existing network. Finally, as highlighted for the previous literature

Section, the infrastructural cost modelling can here also be considered as a potential field of improvement. Table 4 summarises the scientific works reviewed regarding the topic.

Table 4 – Network growth modelling literature review

Reference	Objective	Case Study	Main Methodologies	Infrastructure
Peters et al., 2014	Assess the impact of HSR development on the macroeconomic parameters of community life	USA, Mid-West region	Iterative Long-term User and Community impact model	Fixed predefined network configuration for road, rail, air and HSR
Pablo-Marti et al., 2017	Study the interaction between spatial configuration, demand distribution and choice influence	Four different topographical urban structures	Iterative impact assessment model, based on three different choice rules	No Base network, modelling of weighted road connections in terms of travel costs
Cats et al., 2020	Model the network evolution because of population distribution	Monocentric urban region	Iterative growth model based on 4-step demand modelling and CBA investment assessment	Public transport alternatives (Bus, Light rail, Metro)
Cats et al., 2021	Model the network evolution given different special structures, population distributions, and investment alternatives	Polycentric urban regions	Iterative growth model based on 4-step demand modelling, BCR investment assessment and preferential attachment	Public transport infrastructure with different function hierarchy (Urban, inter-Urban, Regional links)

03

Methodology

London to Paris Channel Tunnel break trough in 1993
France, United Kingdom

3 Methodology

The third chapter of this thesis presents the methodology that is developed to quantitatively study the potential evolution of the future unified European HSR network. The main goal is to outline the sequence of infrastructural investments and their impact on the long-distance transport market of the European Union. Section 3.1 highlights the general approach while Section 3.2 presents the modelling assumptions. The model is finally introduced by explaining the three modules composing it: Input Data module in Section 3.3, the Base Network module in Section 3.4, and the Iterative Growth module in the last Section 3.5.

3.1 Methodology Approach

The proposed methodology follows the approach proposed by Cats et al. (2020) to model growth principles of metropolitan public transport networks. In this study, a novel iterative growth model has been formulated, which firstly generates the potential infrastructural solutions and then analyses the impacts that these solutions have on the travel demand distribution. By assessing the magnitude of these impacts, it is possible to account for changing transportation needs over time and the most beneficial infrastructural investments based on the trade-off between benefits and costs. This allows to iteratively adapt the network expansion to the evolving demand distribution, investment costs and resulting network structures. The following Section details the approach and modelling framework.

The initial step of the model consists in representing the topographical structure of the European continent by means of a hexagonal grid structure, called the MICRO layer grid. This allows to discretize Europe's territory and to represent bigger portions of land trough the hexagons' centroids. Furthermore, each hexagon receives elevation specifications so to obtain a three dimensional terrain configuration. The MICRO grid structure is used to model the infrastructural specifications of potential HSR lines in terms of costs, distance, and path.

Secondly, the major European urban hubs are identified and connected based on their importance, defined by economical output, population, and population density of the country in relation to the case study averages. This creates the MACRO layer grid, which is used to define the possible direct rail connections that can be considered between cities, including existing HSR links, projects under construction or potential connections.

Combining the two layers means that the MACRO grid indicates where a line can be built, and the MICRO grid is used to create the physical infrastructural design for the potential connection. This design returns the travel time, investment cost and distance of the new potential line. This is done for all the potential connections modelled in the MACRO layer grid.

With the accurate representation of Europe in place and the data of future HSR connections available, the potential links are iteratively added to the existing rail network. Their impact is evaluated in terms of generated high-speed rail passenger demand, which is then translated into monetary benefits by calculating travel time savings and externality savings occurred with the modal shift towards HSR. The present value of a potential link is then obtained by weighting the benefits against the investment and maintenance costs of the potential HSR lines.

According to the yearly budget constraint, the best scoring link in terms of Benefit-Cost ratio (BCR) is added to the base network. With the new link in place, the current base network is updates, and the iteration is complete. If there is still some budget left for that year, the model can continue with the investments, by evaluating all links again. If the budget is not enough, the model iterates to the next year to obtain additional yearly budget.

This approach is translated into modelling terms by identifying three main modelling modules: The Input Data module (3.2), the Base Network module (3.3), and the Iterative Growth module (3.4)

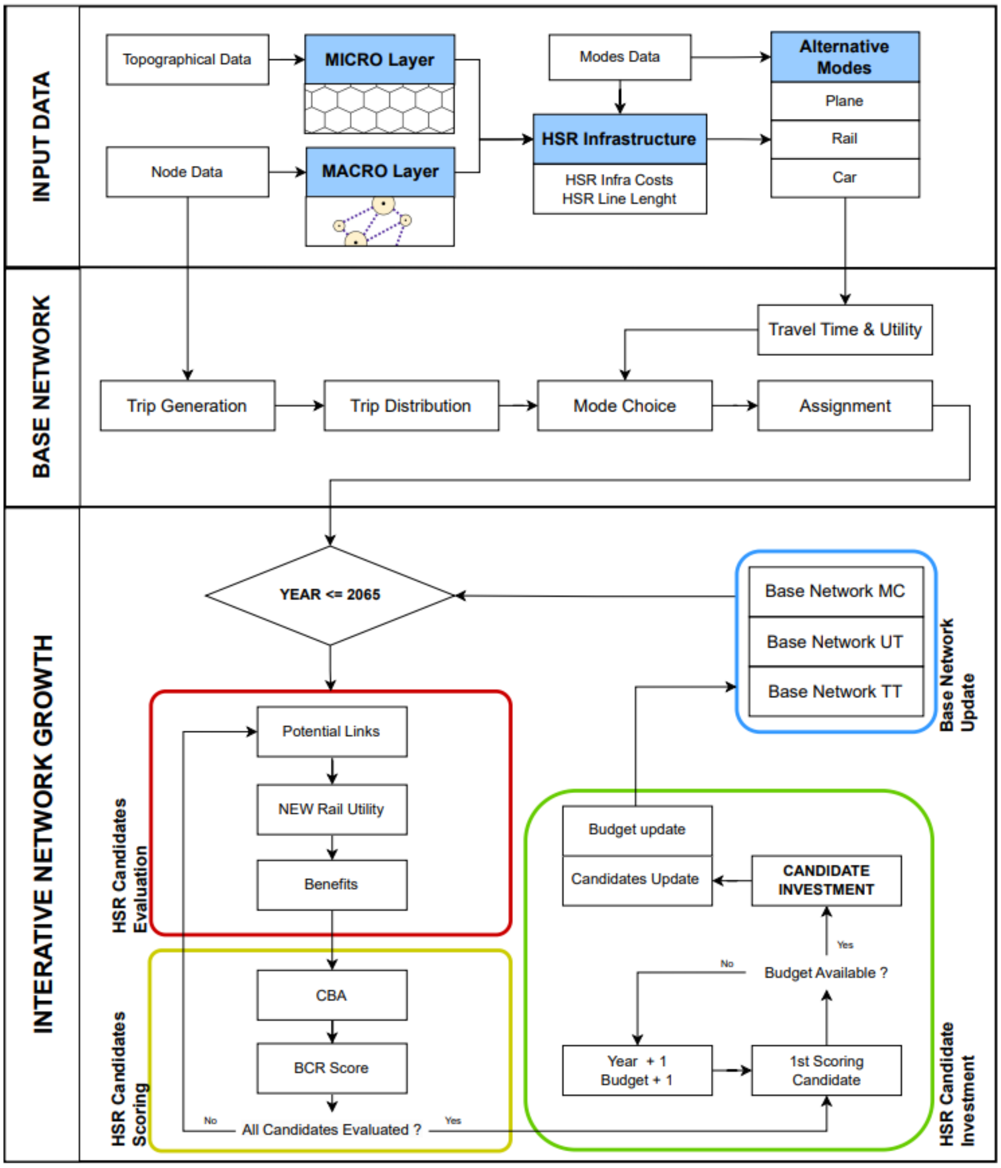


Figure 2 - Graphical representation of the Methodology

The Input Data provides the datasets and main components used in the model, from the grid to the nodes and edges attributes. The Base Network initializes the core component of the model, which contains the network specifications and is updated iteratively every time a link is build. Finally, the Network Growth part is the core Section where the iterations will determine the evolution of the base network given the input data provided.

To replicate the model's outcomes, each of these parts must be initiated individually following the aforementioned order. The first two code packages (input data and base network) remain static and are used as input for the last part, which evolves dynamically throughout the iterations. The chosen modelling language used to build the model is Python, although QGIS has also been used to obtain the elevation of the hexagons. Each passage and Section of the model is detailly explained in the following Sections. Figure 2 provides a graphical overview of the modules.

3.2 List of Assumptions

The model relies on a series of assumptions that allow it to obtain concrete results despite limitations given by its scale. Table 5 provides an overview of the assumptions and of the potential impact that these might have on the modelling outcomes. The final discussion is provided in Section 5.3.

Table 5 - Model assumptions and impact estimation

Assumption	Impact	Implication on results
General		
The model focuses solely on the infrastructural side of the HSR network, therefore excluding the HSR operations and service provision	High	Exclusion of parameters related to mode choice (e.g., price, frequency, transfers), operational characteristics (e.g., line capacity) and economical appraisal (e.g., Operators revenue, track access charges)
The iterative investment allocation process is assumed to be centrally managed, by collecting budget contributions of single countries and allocating funds on a profitability base across the case study	High	Underestimates the coordination issues and national priorities of the different countries involved in the case study, potentially leading results not implementable in practice
Input Data Module		
Infrastructural costs are aggregated into the cost per kilometre	Low	Potentially over or underestimating certain costs categories that are relevant in specific countries
The constructed rail infrastructure is assumed to have the same technical standards across all countries of the case study	Low	Less accuracy during travel time calculations. Less impactful when not considering the service level
Infrastructural design parameters considered: track inclination, speed limits and construction factors related to underground or surface infrastructure.	Medium	Potentially underestimate costs of future HSR infrastructure
Infrastructural design parameters not considered: Station design, intersections with conventional lines, mixed traffic sections, complementary infrastructures (i.e., car bridges, noise barriers)	Medium	HSR line specifications restricted to one design type. No trade-offs between different costs and operational speeds
The model establishes connection between urban hubs. Stations are assumed to be located centrally, whereas airports are georeferenced	Medium	Less accuracy in terms of access and egress travel times, especially for rail
Elevation is the only parameter used to qualitatively describe the hexagonal discretization of the topographical terrain	High	Loss of accuracy in cost calculation and path routing (e.g., Land use not considered)
The population and the economic attributes of urban areas remain static during the time scope considered.	High	Potentially underestimate future ridership potential and thus reduce the profitability of HSR investment in the long-term
Base Network Module		
The modes considered in the modelling process are plane, car, conventional train (<200km/h), high-speed train (>200km/h). Bus is excluded due to its low competitiveness up to 200 km (Donners, 2016)	Low	Given the exclusion of the service layer, excluding bus has no significant impact
Plane and car are assumed to travel directly between OD pairs. Trains instead cross a series of links, whose travel times are summed to obtain the final utility for the OD pair.	Low	Potentially reduces the accuracy during travel time calculations for car and air
Trips are unimodal between origin and destination transport hubs	Medium	Trips are often a combination of multiple modes.
Trips are modelled assuming an uncapacited infrastructure	High	Less accuracy during appraisal: Potentially underestimate the benefits of come investment in relation to improved capacity for other rail option. Potentially overestimate number of passengers on a line
Iterative Growth Module		
'First-in-First-out' investment policy: Most profitable investments are constructed first	Low	Potentially exclude more beneficial investment strategies based on different fund allocation
Cost overruns, delays and external factors are not considered as they depend on a series of hardly predictable political and economic scenarios	Medium	Overestimation of NPV and BCR calculations
If a HSR line is built, it is used as the only rail connection available between the cities its linking.	High	Potentially overestimate travellers shifting from conventional rail to HSR
Induced demand is not considered given the absence of transport service layer, lack of consistent data and broadness of the scope	High	Potentially underestimate travel demand by significant volume
Travel time is the only parameter consider for mode choice	High	Potential inaccurate choice modelling and mode share, influencing investments' profitability

3.3 Input Data Module

The Input Data module aims at generating the necessary data components for the model. Specifically, it provides the modelling of the geographical area and of the HSR infrastructure, respectively through the MACRO and the MICRO layer grids. The former is responsible for establishing which potential rail links are feasible in terms of connectivity, while the latter models the topographical characteristics of the geographical area taken into consideration. Combined, they return the specifications for existing and potential high-speed rail lines in terms of travel time, investment cost and distance. This process resembles the methodology adopted by Levinson et al. (2005), of adopting one layer for the road network and one layer for the land use layer. Figure 3 provides a graphical overview of the two grid structures.

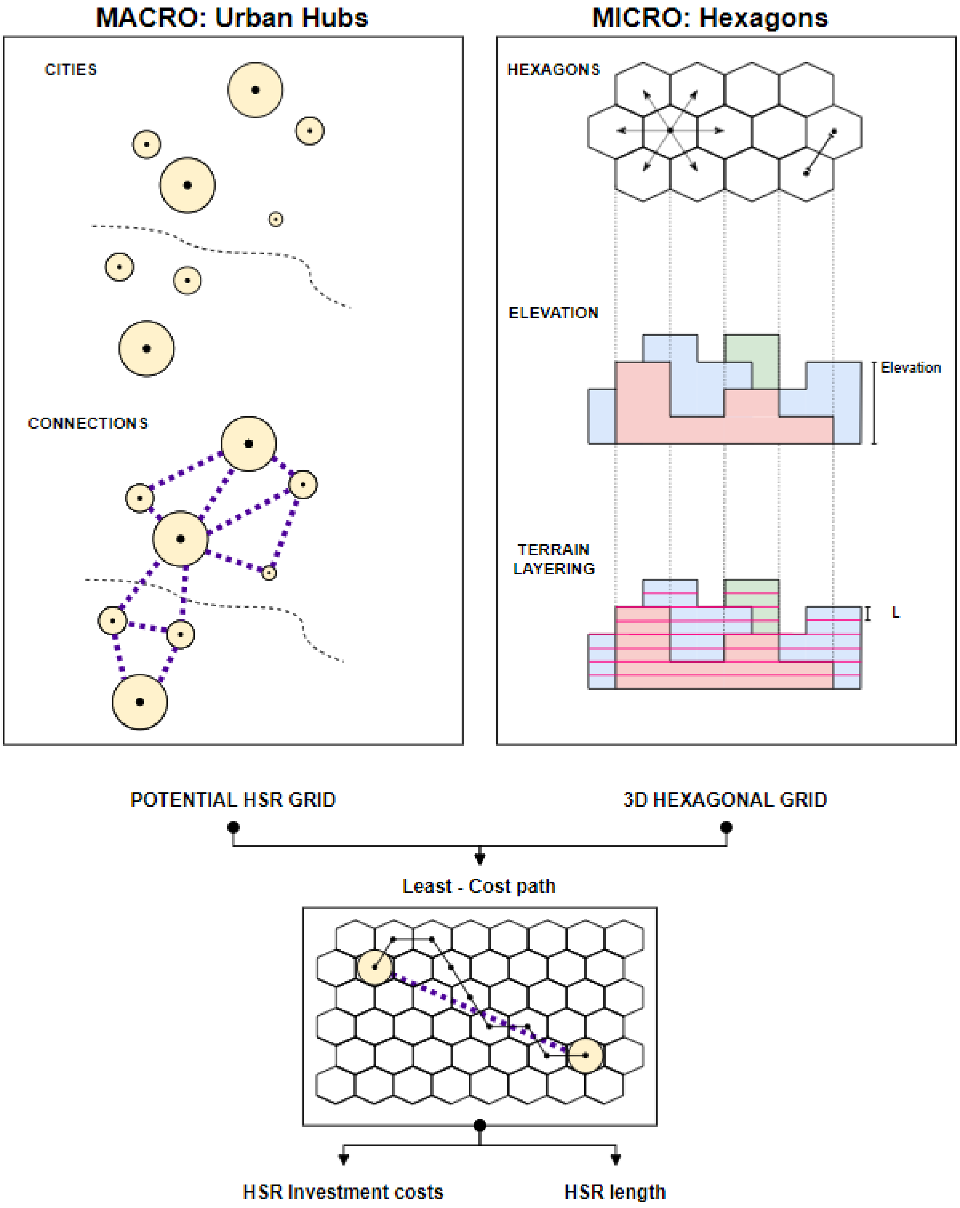


Figure 3 - Input data general overview: Micro and Macro layers

Each of the two grids has different data sets associated to them. The MACRO grid also contains the evaluation parameters that are used to calculate the economic feasibility of the links, whereas the micro level handles all the infrastructural and mode specifications to obtain travel utilities and infrastructural costs. Finally, the combination of the MICRO and MACRO layer will lead to the creation of the current rail network, as well to the creation of the future potential high-speed rail network.

The following Sections highlight the detailed formulation of both grids, with Section 3.3.1 explaining the MICRO layer grid construction with its novel cost modelling, Section 3.3.2 presenting the MACRO layer grid formulation with the novel link determination method, and finally Section 3.3.3 showing how potential HSR investments are obtained.

3.3.1 MICRO Grid: The Modelling of the Geographical Space

The MICRO layer grid represents the discretization of the topographical space of the case study area considered. The methodology chosen to create this grid is Uber's H3 Hexagonal Hierarchical Spatial Indexing system (Uber, 2018), which leverages hexagons for a discrete representation of space. This allows using a hexagon's centroid as a node and the connection between two centroids as an edge. Furthermore, the attributes of the area covered by a hexagon can be aggregated within the centroid itself. The following Sections explain step by step how to build the MICRO layer grid.

I MICRO - H3: Uber's Hexagonal Hierarchical Spatial Index

The H3 hexagonal indexing system, as introduced by Uber in 2018, offers a versatile method to partition geographical areas into hexagons of variable sizes, facilitating in-depth analysis of extensive spatial datasets. Each hexagon is uniquely identified by its centroid, thereby specifying its geographical coordinates and attributes. Hexagons are preferred due to their uniformity in relation to other geometrical shapes; the distance from a hexagon's centre to its neighbours remains constant, simplifying analysis and ensuring smooth transitions. For practical implementation in Python, the h3-py library (PiPy, 2022) provides access to the H3 indexing system.

To create the MICRO grid layer, an initial geographical polygon (geoboundary) of the case study area is created. This polygon can be populated with hexagons using the $h3.polyfill(geoboundary, resolution)$ function of the h3-py library. The resolution level can be chosen based on the level of detail needed for the modelling, which in turn influences the number of hexagons populating the polygon and thus complexity. Each resolution level represents the area of one hexagon expressed in squared km, enabling finer granularity with smaller hexagons or broader coverage with larger ones. The distance between two hexagons' centres can be obtained with geopy.distance (GeoPy, 2023), by calculating the geographical distance between the coordinates of the two centroids.

Once the area has been populated with hexagons, it is possible to distinguish between sea and land points using the $globe.is.land(HexId)$ function of the Globe-Land-Mask library (PyP, 2023). The latter is applied to complete the final grid structure by eliminating all the sea points from the grid matrix. Only the key sea corridors on which potential connections can built, are maintained. These are selected based on existing projects, existing infrastructure or justified infrastructural proximity between the two shorelines, as explained in the following paragraphs.

When building the geographical polygon, there are some land points included in the grid generation that may not belong to the countries chosen within the case study. To get rid of these hexagons, it is possible to use a geojson file containing the polygonal geographical borders of all the countries in the world. The Shapely Python library is then used to transform the hexagon's coordinates into points and check if these points fall within the polygons of the countries within the case study. If not, they are removed.

Finally, the obtained grid matrix contains the hexagons populating the geographical polygon of choice. For each hexagon, its unique alphanumerical identifier, the coordinates and the country of belonging are stored.

II MICRO - Elevation Profiles

Having obtained the set hexagons discretizing the case study regions, the elevation parameter can be added. There are many different methodologies that can be used to pair geographically referenced points to topographical values like elevation. For this thesis, QGIS and Copernicus are chosen, due to the relative ease to manage large datasets and obtain detailed results in reasonable time. This methodology requires the use of Digital Elevation Model (DEM) raster datasets and a grid of points with their geographical coordinates, as obtained in the previous Section. Then, QGIS allows to pair each point of the grid to a value of the elevation raster by using the SAGA's (2023) $Add\ Raster\ Values\ to\ Points$ function. Thus, the hexagon's centroid is paired with an elevation value, indexing all the surface area contained within the hexagonal shape.

Note that one DEM raster covers only a specific area. If the grid of points covers an area bigger than the single raster, then the function must be iterated over different raster until all the hexagons receive an elevation. In this case, the data then needs to be polished and adjusted consequently, to create one single data set of coordinates and elevation values. Finally, the grid matrix is enriched with an additional elevation value paired to each hexagon.

III MICRO - Hexagon Neighbours

With the node properties set, the neighbours of each hexagon need to be defined. This is necessary to understand how edges can be built to create a grid. To find the neighbours, the py-h3 library function $h3.hex\_ring(HexId, 1)$ is used, returning all neighbouring hexagons belonging to a specific degree of closeness. Degree 1 returns all the six closest neighbours of the hexagon, as needed for this study. The obtained neighbour's matrix contains all the hexagons of the grid with their identifiers, elevation, and country values, together with all their neighbouring hexagons and relative data specifications.

IV MICRO – Node Construction: 3D Hexagons with Terrain Layering

The model that is being build, aims at calculating the infrastructural costs of the future potential HSR links into detail. The new lines are built through landscapes with varying topographical characteristics, these being plain, hilly, or mountainous territory. For each of these different terrains, the cost of the infrastructure changes, because it is more complex and costly to build a tunnel under a mountain than a railway on a flat surface. UIC estimated that the average cost of HSR lines mostly composed by tunnels bridge infrastructure is three times higher than the cost of a surface line (UNECE, 2022).

To consider the topographical variations, represented by the hexagons' elevation changes, a novel approach based on terrain layering is introduced. This methodology enhances the hexagonal representation by incorporating additional layers that depict the hexagon's varying elevations, transitioning from a two dimensional to a three dimensional grid. In this way, the spatial discretization can be expanded beneath the surface, incorporating underground elements. This is achieved by introducing a series of parent nodes which replicate the surface hexagon at different underground levels, as shown in Figure 4. Each new node is identified with the same ID associated to the reference hexagon, enhanced by an alphanumerical value indicating the layer ID.

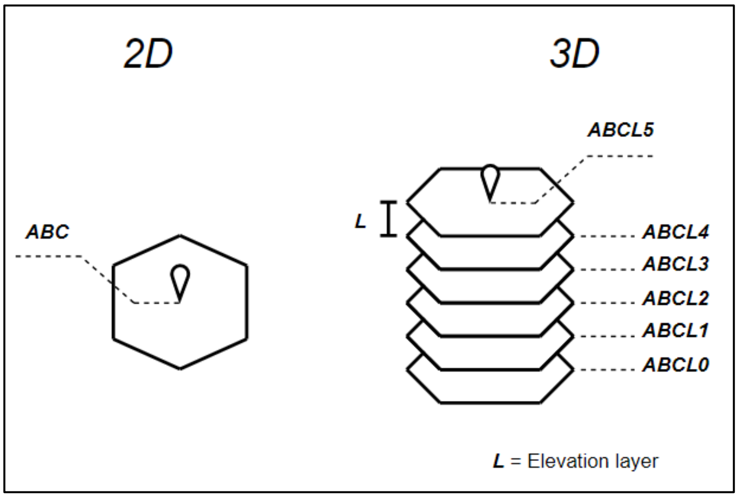


Figure 4 - Hexagon layering process

Having obtained the 3D layered grid, the neighbours definition process is repeated. In this case, special attention must be given the elevation differences between the elevation layers (e.g., distance between ABCL1 and ABCL2 in Figure 4). Centroids are allowed to link each other horizontally, upwards, or downwards, so to replicate real life HSR lines as presented in Figure 5. Therefore, the elevation difference divided by the horizontal distance, determines the steepness of the diagonal edge between centroids on different layers (Equation 1). The latter must be carefully defined, in order to comply with the on the gradient's requirements defined for HSR (UIC, 2015).

$$Gradient\ (\%) = \frac{\Delta Elevation}{HorizontalDistance}$$

Equation 1 - Gradient calculation

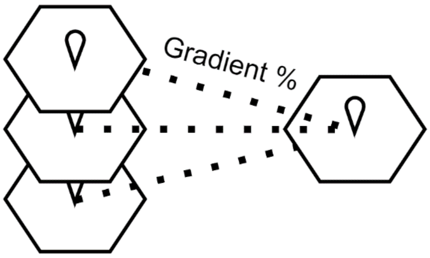


Figure 5 - Possible inter-layer connection

In conclusion, the terrain layering methodology introduced here adds a third dimension to the MICRO layer grid, enabling detailed terrain modelling that incorporates elevation variations into infrastructural calculations. It's important to note that the chosen level of hexagon detail significantly impacts the granularity of the resulting three-dimensional terrain representation

V MICRO – Node Construction: Infrastructural Costs

The layering of the terrain allows assigning different cost weights to the nodes on the surface or underground layers, indicating how much it will cost to build HSR infrastructure trough the hexagonal surface or underground area indexed. Defining the cost for each centroid is a difficult process, due to the influence of multiple factors. As the European Court of Auditors (2018) extensively explained for the European case, each project is unique and its completion subject to political pressure, poor coordination, and the impact of different design choices. This is without considering the natural obstacles that vary greatly from project to project. The cost calculations are thus inevitably related to the specific social, geographical, and economical contexts, which are difficult to translate into normalized modelling parameters.

Figure 5 provides a graphical overview of how such cost variability looks like among existing infrastructure. It can be noted that the cost per kilometre does not only oscillate between different countries (e.g., Belgium and Japan), but also has huge variations within countries themselves (e.g., Italy). By analysing the scientific literature, three main factors influencing the final HSR infrastructural costs can be identified (Campos et al., 2007; UNECE, 2022; Barron et al., 2009). The first and most important one, relates to the terrain conformation which the HSR line must cross. As already mentioned before this has a significant impact by tripling or quadrupling the cost of normal surface infrastructure. In Figure 5 this is pretty evident for Italy, where HSR on flat grounds costs four times less than building tunnels trough mountainous terrain of the Alps or Apennines.

Secondly, population density also plays a huge role affecting land costs and compensative infrastructure. For example, in Figure 6, it is possible to note how Spain and France, which have big urban centres but relatively empty rural areas, have lower costs as compared to the Netherlands or Germany, where higher population densities can be found outside the cities.

Lastly, the infrastructural design choices of single projects can influence the final investment needs. France for example makes use of higher gradients to avoid tunnels, whereas in Italy a great number of over structures is built to compensate for crossing densely populated areas. Station construction also greatly affects the final cost, but this is not considered addressed specifically but rather as part of the average cost of the infrastructure per country.

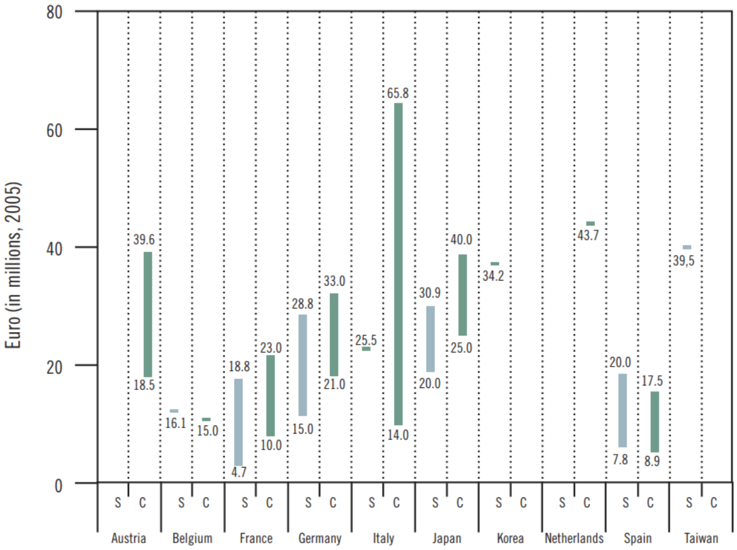


Figure 6 - Average high speed rail Euro per kilometre for existing infrastructure. S = Line in service, C = Lines under construction. (Barron et al., 2009)

Therefore, obtaining the final cost per kilometre requires a cautious approach towards making estimations from current data. Furthermore, the figures of the previous paragraph strictly refer to a small group of countries which already have HSR networks, making it even more uncertain to forecast such costs for nations that will develop new infrastructure in the future.

To formulate a consistent approach based on available data, this thesis proposes a novel two step cost estimation methodology. Firstly, the average construction costs per kilometre for both surface

($\overline{Cost\_pkm\_Surface}$) and underground infrastructure ($\overline{Cost\_pkm\_Underground}$) are obtained for the case study. These averages are based on data of existing infrastructure available in literature.

Secondly, the average costs are scaled for each country (c) based on four factors: Terrain conformation (T_c), population density (D_c), national GDP ($GDPpc_c$), and Price Level Index (PLI_c). The first two are among the most relevant factors affecting HSR costs, GDP per capita represent the potential spending power of a nation, while PLI provides more insight on the cost of living and therefore the potential material, labour and infrastructural costs specifications per country. These four parameters are scaled against the averages of the case study (Equation 2), and their mean value multiplied by the average costs of surface (Equation 3) and underground (Equation 4) constructions.

$$Cost\_Weigth_i = \overline{(\frac{T_c}{\overline{T}} + \frac{D_c}{\overline{D}} + \frac{GDPpc_c}{\overline{GDPpc}} + \frac{PLI_c}{\overline{PLI}})}$$

Equation 2 - Cost weight calculations for each country

$$Cost\_pkm\_Surface_c = \quad Cost\_Weigth_c * \overline{Cost\_pkm\_Surface}$$

Equation 3 - Country specific cost pkm for surface nodes

$$Cost\_pkm\_Underground_c = \quad Cost\_Weigth_c * \overline{Cost\_pkm\_Underground}$$

Equation 4 - Country specific cost pkm for underground nodes

Regarding the design choices, which play a significant role in defining the technical specifications of the lines, this thesis considers only the steepness gradient. Other technicalities, as curvature radius, signalling systems and urban designs are significantly more difficult to model on the macro level and thus deemed to be outside of the scope.

The sea infrastructure, meaning bridges and tunnels, is instead modelled manually. Usually, these projects present unique characteristics in terms of infrastructural design and costs, and in the European case their number is also very limited. Each sea stretch that could be considered feasible for the construction of HSR infrastructure, selected based on existing projects or land proximity, is graphically analysed and its hexagons added to the MICRO layer grid. For existing projects, the costs can be retrieved from project figures, whereas for potential connections without any reference, projects of similar design (in terms of distance) can be used for the cost calculations. In modelling terms, the sea infrastructure is added assuming an elevation value of 0, while the cost per kilometre is calculated considering the length of the edges needed to connect the sea centroids to the rest of the grid. For example, if four hexagons totalling a distance of 24 kilometres are needed to replicate a potential bridge of 20 kilometres, then five edges are added for a total of 24 kilometres. The costs of the sea infrastructure are thus spread out accordingly along the newly obtained distance. Once the hexagons are added and the cost per km obtained, the corridor has been properly mapped.

VI MICRO - Edge Construction: Building the HSR Infrastructure

To complete the three dimensional grid structure, the layered nodes are connected by building weighted edges between them. To calculate the assigned weight, the average of the two centroids' (i.e., i, j) cost value is multiplied by the distance between the nodes, as shown in Equation 5.

$$Wedge_{i,j} = \frac{Wnode_i + Wnode_j}{2} * Distance_{i,j}$$

Equation 5 - Cost weight assigned to each edge

This makes it possible to have diagonal and horizontal connection between centroids on different layers, simulating the construction of HSR structures across the network that can rise or descend through different elevation profiles. The combination of these edges generates then the final path of the potential HSR infrastructure from one origin node to one destination node.

A graphical representation is shown in Figure 7. The bold black lines highlight the portion of surface infrastructure suitable for HSR infrastructure, whereas the dotted lines show the potential underground HSR connections. Finally, from a surface node to an underground node, a half-dotted edge shows a tunnel portal.

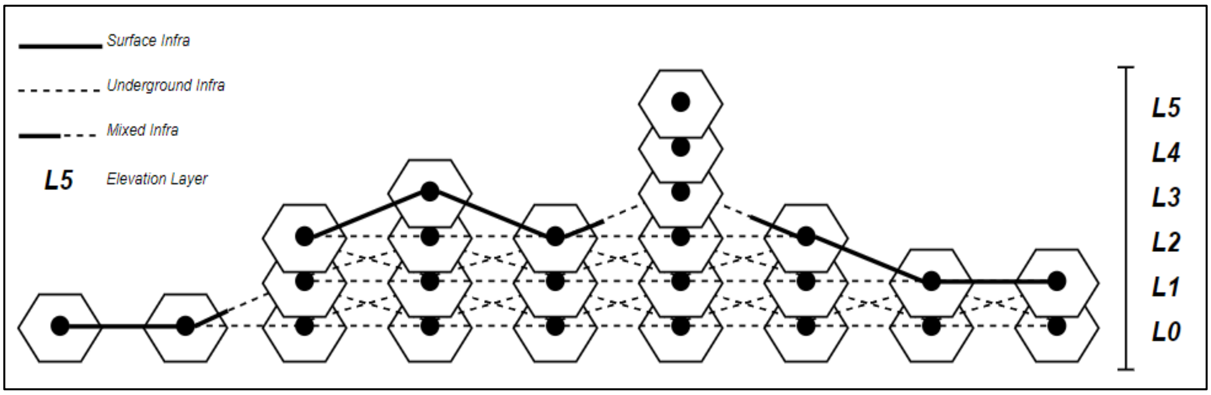


Figure 7 – Three dimensional MICRO layer grid

Three types of edges are therefore created, based on the nodes they are connecting. Two surface nodes are connected by a surface edge while two underground nodes are linked by an underground connection. For links between a surface and an underground node, a mixed infrastructural edge is initialized, which represents the entrance or exit portal of a tunnel. Having built the grid of weighted nodes and the edges to from a three dimensional representation of the terrain, NetwrokX's graph function (NetworkX, 2023) is used to model such configuration. This concludes the creation of the weighted MICRO layer grid, which is used to model the potential HSR lines as an outcome of terrain conformation.

3.3.2 MACRO Grid: The Modelling of the Urban Distribution

The MACRO layer grid is the set of nodes and edges that replicates the demographical distribution across the geographical area considered, describing how population is spread and concentrated across regions. For an appropriate discretization of such distribution, the major population centres become the nodes and the connecting edges represent the rail links between them. As for the hexagons, the nodes are geographically indexed and aggregate the main attributes of the urban population they are representing. The following Sections explain step by step how to build the MACRO layer grid.

I MACRO – Nodes Construction: The Selection of Urban Hubs

The nodes are identified as the major urban hubs present across the geographical area of scope. The selection criteria for a hub to be considered, is based on the methodology used by Donners (2016), who scored cities based on population, local GDP, and level of higher education. The relevance of each population hub is assessed based on how good or bad it scores compared to the average values of the country of belonging and the complete dataset. The overall score is obtained by summing the relevance values of each criterion with a weight factor, to prevent for example small cities with high number of students to outperform bigger economical centres.

The size of the obtained set of cities can be further reduced by considering a minimum threshold score. Additionally, based on the practice in the air industry of considering close centres of importance as single zones, it is possible to aggregate different cities into one population centre. The closeness degree considered for this case is the 25-30 km catchment area of high-speed rail stations, allowing to further aggregate cities that are closer than this threshold. Additional population nodes can be added manually to include important logistical hubs that do not score sufficiently high enough.

For all the cities obtained, several parameters are considered. Together with population, GDP per capita, and geographical coordinates, each node of the MACRO layer grid is paired with a node of the MICRO grid. This means assigning to each city the unique identifier of the closest geographical hexagon, as well as the elevation layer identifier based on the altitude at which the city is located. Furthermore, the following parameters complete the definition of the MACRO layer nodes:

- Language and country
- Within Schengen area or no
- Country population
- surface
- City density calculated as the total urban population over the country's surface

The final city selection constitutes the set of nodes of the MACRO layer grid and provides all the necessary information regarding the population hubs considered for the study.

II MACRO – Edge Construction: Establishing the Rail Links

After having defined the nodes of the MACRO layer grid, the edges connecting them are initialized. These links are defined as the rail connections that one node can have with its neighbouring nodes. Previous studies (Donners, 2016; Grolle, 2020) have used the current TEN-T policies as reference for their infrastructure (European Commission, 2013). This thesis instead aims at analysing all existing and potential rail connections without a predefined infrastructural scheme, by developing a novel methodology for the establishment of rail links between urban hubs. This allows having more freedom in making design choices in the long-term.

The methodology proposed assumes that cities can connect to other urban hubs based on their influence range, which is proportional to the GDP per capita and the population, but disproportional to urban density, obtained as the ratio of urban population compared to the country's surface. This allows for two connection principles. Firstly, big and economically influential cities can establish connections over a wider range than smaller and less economically influential cities. Secondly, if a city is in a country with a high density of cities (e.g., the Randstad in the Netherlands), its connection ability is reduced. The latter mechanism is implemented to have a trade-off between the number of connections and computational complexity

In modelling terms, this means that each city (i) receives an influence weight, obtained as the square of the ratios between the city's population (P_i), GDP per capita ($GDPpc_i$) and the country's urban density

($Urban\_D_c$) against the average values of the case study area. The urban density is calculated by dividing the total urban population by the area of the country, obtaining an indicator of the urban area influence in relation to the country's dimension. Secondly, the weight is then multiplied by a predefined distance parameter d to obtain the radius of the influence circle area reachable from the node. This distance parameter d must be calibrated to the specific scenario (Section 4.4.1). The square is applied to reduce the presence of outliers and to reduce the difference between extremes of the scale. The radius of influence of each city is obtained according to Equation 6.

$$Reach_i = \sqrt{\frac{\frac{P_i}{P} * \frac{GDPpc_i}{GDPpc}}{\frac{Urban\_D_i}{Urban\_D}}} * d$$

Equation 6 - Radius of the influence area of each urban hub

With the formula explained above, cities are linked between each other if the relative influence circle areas are touching or overlapping, thus when the summation of the radii ($Reach_i + Reach_j$) is equal or greater than the distance between cities. The distance parameter d must be carefully calibrated within the case study. Values that score to high return a substantial number of links that may be redundant, whereas lower values may exclude connections. A city must relate to all its potential neighbours, but at the same time the number of links must be controlled to avoid unnecessary complexity. Furthermore, the connection possibilities will determine the future capabilities of the model, as the influence radius establishes the evaluation horizon of the modelling process.

The edges of the MACRO layer grid represent therefore the possible rail links between cities (nodes), based on the importance that each city has in relation to the surrounding geographical area. The network for alternative modes, such as plane and car, is not modelled. This relies on the assumption that both car and plane can freely travel between OD pairs, while train must traverse a series of nodes to reach its destination.

The final obtained set of links contains all the necessary information about the potential rail connections between urban hubs. Also in this case, NetworkX's graph function (NetworkX, 2023) is used to create the MACRO layer grid structure that models the demographical distribution and the relative rail connections between urban hubs. The obtained grid is used to model the rail network and evaluate the current performance of conventional rail, establishing where HSR can be potentially build.

3.3.3 MICRO & MACRO Layers: The Construction of the HSR Infrastructure

With both the MICRO and the MACRO grids in place, the final HSR infrastructure can be obtained. In this last phase of the Input Data module, the modelling of the geographical area and of the urban distribution are merged into one single layer. To build HSR infrastructure the following approach highlighted in Figure 8 is used.

1. Each city node (MACRO) is paired with the geographically closest hexagon centroid (MICRO)
2. Dijkstra's weighted shortest path (NetworkX, 2023) is used to get the sequence of hexagons that link the cities index through the centroids by using the MICRO layer grid
3. The path returns the infrastructural costs as the sum of the edges' weights, and the length of the infrastructure as the number of hexagons traversed multiplied by the distance between two centroids.

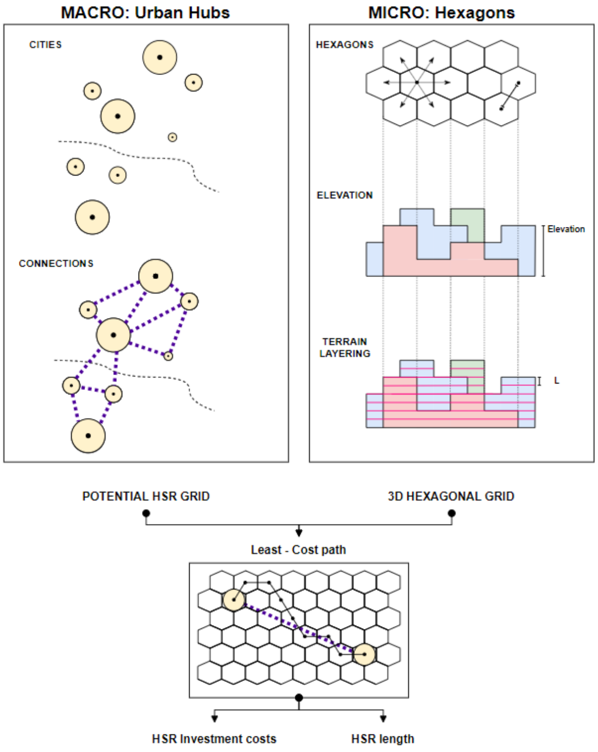


Figure 8 - MACRO and MICRO layer grids return the infrastructural specifications of the potential HSR lines

The set of links is thus expanded with the information regarding the infrastructural costs and length of the links. This concludes the first input data Section and paves the way for the second modelling step, the Base Network module creation.

3.4 Base Network Module

The second modelling step aims at initializing the transport demand patterns for all OD pairs, in preparation for the iterative modelling, which will serve as the current transport scenario at step 0. In detail, the Base Network defines the transport mode alternatives, and how these alternatives perform in the current transport network structure in terms of travel time and travel utility. In modelling terms this means defining the mathematical formulas to compute the utilities between the nodes of the MACRO layer grid. For this purpose, three alternative transport modes are chosen: car, plane and conventional rail. The bus option is excluded as it is competitive only up to 200 km (Grolle, 2020), not in line with the long-distance transport study aim of this work.

The methodology used to obtain the Base Network, is centred around the traditional Four Steps Transportation Modelling approach (Ortúzar et al., 2011), and relies on three main modelling assumptions. Firstly, only travel time is considered for the calculation of the generalized transport costs. Additional utility components such as ticket prices, fuel and comfort are not considered. This assumption reflects the lack of data that could be consistent over all the counties of the case study and reliable over the time frame considered. The travel utility is thus defined as the summation of all the weighted travel time components.

The second assumption states that trips refer to one-way journey from an origin to a destination. As can be seen in Figure 9, there are two trip modalities: by car and air, or by rail. The former can directly link an origin to a destination, whereas the latter may cross multiple nodes and edges to connect an origin to a destination. This assumption allows to model travel times of the rail infrastructure in more detail. For air and car, travel times are assigned on an OD pair basis, whereas for rail the final travel time for an OD is the summation of the single links' travel times. Figure 9 explains the concept graphically.

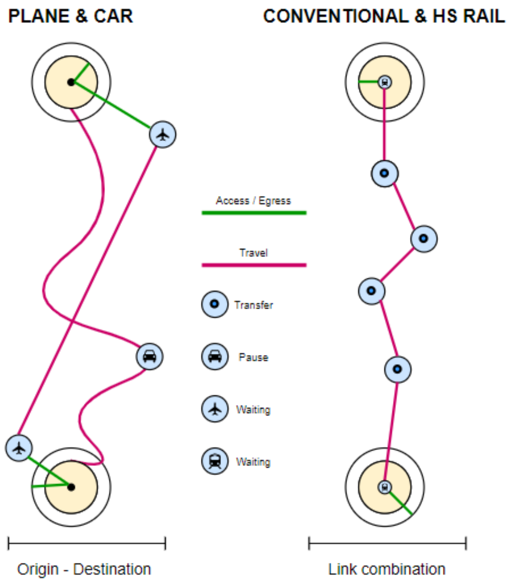


Figure 9 - Network structure assumptions of the different modes

For the last assumption, rail is considered as a single mode, but it can have two different performance levels in terms of conventional and HSR capabilities. The previously introduced modularity of the rail network is used to assign higher or lower travel times to each link. During the Base Network creation, it is thus possible to initialize distinct types of existing rail connections, by including or excluding HSR travel times. Thus, each link is assumed to be either a conventional or high-speed rail connection.

The modelling outcomes will provide the current transport specifications along the MACRO layer grid, in terms of travel time, travel utilities, mode choice and mode specifications. The obtained transport network configuration is then used as a starting point for the iterative evolution. Each of the data sets initialized within the Base network creation are constructed as adjacency matrices notifying connections between cities.

3.4.1 Travel Time & Weighted Utilities

As explained in the Section above, only time is used to evaluate the final utility of a trip, which is obtained for each mode by considering different travel time components. For example, travelling by plane implies longer waiting times for security checks and boarding procedures, whereas rail has better access and egress times. Travelling by car is even more comfortable, although travel times can be higher due to breaks and traffic congestion.

Trips are therefore a combination of distinct stages, each having its own weight on the final perception that travellers have of travel time. This in turn influences the mode choice when planning a trip. To include the importance of the different trip stages, the utility is obtained by the summing of the weighted travel time components for each mode. The weights thus reflect the total perceived disutility of the different trip stages. These are defined based on Grolle (2020) and follow the assumption on the service level of Section 3.2. The trip is divided into access, waiting, in-vehicle and egress stages. Each of them receives a weight in relations to in-vehicle time. Table 6 shows the mathematical formulation of the weights to be applied to travel time utility.

Table 6 – Weights associated to each trip stage

	Access	Waiting	In-Vehicle	Egress
VOT	VOT_C^{ACC}	VOT_C^{W}	VOT_c	VOT_C^{EGR}
Weight	$w_{ACC} * VOT_c$	$w_W * VOT_c$	1	$w_{EGR} * VOT_c$

Concerning the different modes, car and plane utilities remain static throughout all the iterative evolution process. On the other hand, rail utility Is dynamic as the investment in HSR links improves the travel time over time. The following Sections better describe the parameters taken into consideration when calculating the travel time and the final utility for each transport mode.

I Plane

Planes directly connect the airports of the origin and destination cities. For the final utility, additional parameters describing access time, egress times and waiting time are considered. Transfers for plane are assumed as non existing, and each city is matched with IATA-listed airports to ensure the infrastructure is open for commercial operations.

Nevertheless, some restrictions are applied. Travel time and utility calculations for plane trips are performed only for the OD pairs that satisfy a distance and passenger flows threshold. Donners (2016) provides a realistic minimum air route usage of 25000 yearly passengers. For the distance threshold, Eurocontrol data (Eurocontrol, 2022) shows that short-haul connections of the main air carriers of Europe fly average distances of 500 km, whereas a research of Air Sector One in 2021 shows that the shortest flights of the main European carriers below 300 km are just cross-sea air connections. Therefore, the distance threshold is adjusted to 300 km. This avoids very short and unrealistic flight options but allows to consider short connections that cross mountain ranges for example (e.g., Milan-Munich).

The travel time for plane is obtained dividing the great-circle distance between origin (i) and destination (j) by the average speed of air travel. For plane no detour factor is applied, as it is assumed that trips with this mode are not significantly influenced by potential obstacles. This in line with the estimations performed by Donners (2016), while the calculations are reported in Equation7.

$$TT\_Air_{i,j} = \frac{GCD\_Air_{i,j}}{Speed_{AIR}}$$

Equation 7 - Plane travel time calculations

The calculated travel time is further described by additional time components that form the weighted travel time utility of a trip. Access and egress time parameters $(ACC_Air_i, EGR_Air_j)$are obtained from the OpenRouteService API (OpenRouteService, 2023), which allows to calculate real world car travel times given two locations. Waiting time is added both before the trip $(Wait)$, in terms of security checks and plane onboarding procedures, as well as after the trip $(ExWait)$, for baggage collection and exiting the arrivals. Each time component is then multiplied by a weight defining its importance within the trip $(w_{INV}, w_{WAIT}, w_{ACC/EGR})$, as presented in Equation 8.

$$UT\_Air_{i,j} = w_{ACC/EGR} * ACC_{Air_i} + w_{WAIT} * Wait + w_{INV} * TT\_Air_{i,j} + w_{WAIT} * ExWait + w_{ACC/EGR} * EGR\_Air_j$$

Equation 8 - Plane weighted travel utility calculations

II Car

The car option represents the private mode of transport that is used for door-to-door travel. The travel time ($TT\_Car_{i,j}$) is obtained by using the OpenRouteService API (OpenRouteService, 2023), as done in by Grolle (2020). This allows to have accurate travel time values for city centre to city centre journeys expressed in hours.

For the weighted utility calculations, a detour factor ($Detour_{CAR}$) is considered and pause time is added ($Pause_{CAR}$) as a share of the in-vehicle time. This allows to consider additional travel time in case of congestions, additional distance and stopping moments. The final weighted utility for car is calculated for an origin (i) to destination (j) pair basis and remains static during the entire network growth stage. The utility calculations are reported in Equation 9.

$$UT\_Car_{i,j} = w_{INV} * (TT\_Car_{i,j} * Detour_{CAR}) + w_{WAIT} * (TT\_Car_{i,j} * Pause_{CAR})$$

Equation 9 - Weighted travel utility calculations for car

III Rail

Rail is the transport option to travel between stations of different cities. As already explained, the travel path for this mode may require the crossing of multiple nodes and edges while travelling between origin and destination. Each edge has a dynamic travel time assigned to it that switches from conventional to HSR once an upgrade investment is carried out on that link. Thus, two different travel times need to be calculated.

For conventional rail, each edge of the MACRO layer grid receives a travel time weight. In an ideal situation, a free travel time API as used for car would be the most accurate choice, but unfortunately such tools are not available for rail currently. At the same time, dividing the greater circle distance by an average speed is also not an option, as terrain factors hugely change travel times over the same linear distances. Furthermore, this thesis aims to study the effects of terrain variations over the infrastructural designs, thus the base network specifications for rail need to be as accurate as possible to replicate such variations in terms of travel time. Therefore, it is assumed that a relationship between car and conventional rail travel times presents a more accurate solution to estimate the latter. By considering that the distance travelled with car is equal to the rail one, and assuming an average rail speed ($Speed_{RAIL}$) it is possible to obtain the travel time for rail. A detour factor ($Detour_{RAIL}$) is considered also in this case, to correct travel times and achieve more accurate results. Calculations are reported in Equation 10.

$$TT\_Conventional\_Rail_{LINK} = \frac{TT\_Car_{LINK} * Speed_{CAR}}{Detour_{CAR}} * \frac{Detour_{RAIL}}{Speed_{RAIL}}$$

Equation 10 - Conventional Rail travel time calculations

For HSR, the travel times the calculations are different. The length of potential HSR infrastructure has been obtained in Section 3.2.3. By dividing the obtained distance ($Distance_{HSR-LINK}$) by an average speed ($Speed_{HSR}$), the HSR travel time is obtained. The detour factor for HSR ($Detour_{HSR}$) defines the final travel time value, as shown in Equation 11.

$$TT\_HSR\_Rail_{LINK} = \frac{Distance_{HSR-LINK}}{Speed_{HSR}} * Detour_{HSR}$$

Equation 11 - High-Speed Rail travel time calculations

It must be noted that the travel times for HSR infrastructure are calculated using equation 11 also to initialize existing HSR lines. The reason is to be consistent with the scope of this thesis, which assumes equal standards for all the countries, in contrast to reality where HSR infrastructure are built following different national design parameters. Transfers in rail are not considered for two main reasons. Firstly, there is a general lack of consistent data across the case study, as train travel time is not obtained from revealed data sources. Secondly, by focusing on the infrastructural side of HSR, all the specifications concerning the service level definition and provision are be left out of the study.

The process of calculating the rail utility is different from car and air travel. In this case there is no direct connection between an origin or destination, but rather a combination of links that form the chosen route between two cities. Therefore, to obtain the final travel time for each OD ($TT\_Rail_{i,j}$), the weighted shortest path is used in the MACRO layer grid, returning the summation of the travel times of each link. Each of the edges included in the path can be either initialized with conventional rail travel times, or, if an investment is performed, with HSR travel times ($TT\_HSR\_Rail_{LINK}$ or $TT\_Conventional\_Rail_{LINK}$). This allows to dynamically model the rail utility along the routes, as modelled in equation 12.

$$TT\_Rail_{i,j} = Dijkstra_{i,j}$$

Equation 12 - Rail ravel time calculations

Once the in-vehicle time is obtained, access, egress and waiting time factors are added and all components weighted. Waiting time is added to model the time spent at stations finding the platform and preparing to board the train, while the exiting waiting time is assumed to be irrelevant. Access and egress time for rail are modelled following the methodology adopted by Grolle (2020), who assumes that the size of the metropolitan area is the normative factor for variability for time. By assuming that the urban area can be modelled as a circle and that the station is located in its centre, this means that smaller cities will have lower rail access and egress parameters as compared to bigger ones.

The size of an urban area can be expressed by the radius (r_i) of the circle, as shown in Figure 10, from which it is possible to derive the average distance of a point from the centre as 2/3 of circle's radius. Grolle reduces this distance to 1/4 of the radius by considering higher urban densities towards the centre and higher averages speeds on the peripheral areas of the city. By additionally considering an urban detour factor ($Detour_{CITY}$) and an average speed ($Speed_{CITY}$), the average access and egress time parameters for rail stations (ACC_Rail_i, EGR_Rail_i) can be obtained with Equation 13.

$$ACC\_Rail_i = EGR\_Rail_i = \frac{\frac{1}{4} r_i * Detour_{CITY}}{Speed_{CITY}}$$

Equation 13 - Access and Egress time calculation for train stations

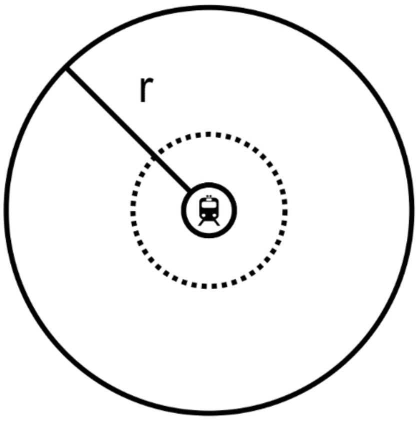


Figure 10 - Urban area assuming the centrality if the rail station

With all parameters calculated and the relative weights applied, the final weighted rail utility is obtained with Equation 14.

$$UT\_Rail_{i,j} = w_{ACC/EGR} * ACC\_Rail_i + w_{WAIT} * W\_Rail_i + w_{INV} * TT\_Rail_{i,j} + w_{ACC/EGR} ** EGR\_Rail_j$$

Equation 14 - Weighted travel utility calculations for Rail (HSR + Conventional)

Once having defined all the mode parameter considered and how to compute both travel time and travel utility, the fours step model can be introduced.

3.4.2 Trip Generation

The first stage of the four-step model calculates the potential yearly trips that one city node can generate. The interpretation and mathematical formulation of Donners (2016) is used. As reviewed by the author, the choice of making a long-distance trip differs from the one of making shorter distance one, therefore other travel parameters and zonal data must be considered. Firstly, the urban hubs considered in the case study are enhanced by defining the large metropolitan, also know as the Functional Urban Area (FUA). This allows to incorporate also the population living outside the city border that is still within the commuting area. Statistical data is therefore captured more conveniently and represents better both the spatial extend and the functional dynamics in terms of the region's economy, transport systems and population distribution. Furthermore, by considering the metropolitan nature of hubs, the evaluation of potential infrastructural investments can be assessed on a large regional scale.

The main assumption while formulating the trip generation is that each city's attraction (A_i) equals the city's production (P_i), achieving symmetry between travellers in both directions. The population of each metropolitan area (Pop_i) is multiplied by the number of long-distance trips that an average European undertakes each year (t). The number of trips is then adjusted with the ration between the GDPs per capita ($GDPpc_i$) of each city and the average GDP per capita of the case study ($\overline{GDPpc}$). This measure of per capita income is considered as a principal factor in determining the quantity of long-distance trips that a person is able and willing to undertake (Aparicio, 2016). Equation 15 provides the mathematical formulation.

$$A_i = P_i = \frac{GDPpc_i}{\overline{GDPpc}} * t * Pop_i$$

Equation 15 - Trip generation (Donners, 2016)

3.4.3 Trip Distribution

In the second stage, the trips previously generated are distributed to predict traffic flows between the OD pairs of the case study. As in trip generation, Donners (2016) provides the formula to calculate the trip distribution, which is based on the traditional gravity model and enhanced by including travel barriers between origin and destination. The latter are especially influential when considering long-distance trips, as borders are still perceived as obstacles to overcome when travelling. Specifically, Donners considers language borders, territorial borders, Schengen and federal borders, which make people less likely to perform trips. For each OD pair, each barrier is analysed and if present, is added to the total barrier value ($\beta_{i,j}$). Subsequently the barrier value is multiplied with the distance impedance ($D_{i,j}^{k}$), therefore increasing the friction factor between cities. Donners has estimated each barrier value, as well as the constant l and the distance sensitivity k, on a set of OD pairs for which traffic flows are known. For trips crossing multiple borders, it is assumed that only the barriers characteristics of origin and destination are effective. Equation 16 shows the trips volumes ($V_{i,j}$) obtained with this methodology based on the origin and destination population (P_i, P_j).

$$V_{i,j} = P_i * \ P_j * l * \frac{1}{D_{i,j}^{k}} * \frac{1}{\beta_{i,j}}$$

Equation 16 - Trip Distribution (Donners, 2016)

For this study, two changes are made to the proposed trip distribution method. Firstly, the federal barriers are not considered. The reasoning assumes that HSR has the great potential to reduce physical and psychological distances between people. So federal barriers would potentially be the first one to fall in case a new HSR line is built. Secondly, the methodology proposed by Donners (2016) is modified by transforming the gravity model into a doubly constrained gravity model (Ortuzar, 2011). This change is implemented to ensures that all trips generated by a location are distributed, in contrary to the previous formulation where trip generation and attraction were considered as an input rather than as a constrain for trip distribution. Equation 17 introduces the general formula of the revisited trip distribution approach based on Donners, showing the socio economic adjustment factor ($K_{i,j}$), the friction factor ($F_{i,j}$), the attraction of each destination (P_j) and the production associated to the considered origin (P_i).

$$V_{i,j} = P_i * \frac{P_j * F_{i,j} * K_{i,j}}{\sum_{j=1}^{n} P_j * F_{i,j} * K_{i,j}}$$

Equation 17 - Doubly Constrained Trip Distribution

Given the availability of the data and following Donners' formulation, an inverse power formula based on distance is used for the friction factor, in the form of $F_{i,j} = \ D_{i,j}^{-k}$. The socio economic adjustment factors considered are the barriers ($\beta_{i,j}$) and the balancing constant (l) from Donners, therefore obtaining $K_{i,j} = \frac{l}{\beta_{i,j}}$. By substituting all elements of Equation 17, the new formulation for the doubly constrained trip distribution model is obtained in Equation 18.

$$V_{i,j} = P_i * \frac{A_j * \frac{1}{D_{i,j}^k} * \frac{l}{\beta_{i,j}}}{\sum_{j=1}^{n} A_j * \frac{1}{D_{i,j}^k} * \frac{l}{\beta_{i,j}}}$$

Equation 18 - Doubly Constrained Trip Distribution

Subsequently, by iteratively balancing the attraction and production factors of the trip distribution matrix, convergence is reached, and the trip distribution is obtained. Note that attraction equals production, as attraction can be hardly obtained due to the inconsistency of data given the geographical scope of the thesis. Finally, trip distribution returns the number of trips that are made on a yearly basis between two cities.

3.4.4 Mode Choice

Within scientific literature there are several choice models available to compute the probability of choosing a mode based on weighted travel time utility. To remain in line with the previous formulations adopted from Donners (2016), the Random Regret Minimisation choice model (Chorus, 2010) is considered. This choice is motivated by the limited data availability and by the fact that RRM slightly outperforms RUM counterparts concerning travel mode and route choices. Furthermore, RRM seems to favour strong performances and increase choice probability for the ‘in between’ option (Chorus, 2010).

The time values used as the utility parameters have been obtained following the approach explained in Section 3.4.1. The final modal split for each single travel mode considered is thus obtained based on the trade-off between the weighted door-to-door travel utility of the reference mode (UT_m) against all other modes (UT_n). The systematic regret (R_m) for each mode is obtained with a Logsum of the utility differences adjusted with a travel time taste factor (β_{TT}). The formulation is presented in Equation 19.

$$R_m = \sum\nolimits_{n \neq m} \ln \left(1 + e^{\beta_{TT} * (UT_n - UT_m)}\right)$$

Equation 19 - Systematic Regret (Chorus, 2010)

With the regret values calculated, a variant of the multinomial-logit formulation is used to obtain the final mode share, as shown in Equation 20.

$$P_m = \frac{e^{-R_m}}{\sum_m e^{-R_m}}$$

Equation 20 - Mode share calculations

Finally, the mode choice is obtained for each OD pair, establishing the ridership values for each of the modes considered. This step further defines the base network scenario in terms of people flows and mode specifications.

3.4.5 Trip Assignment

The previously generated demand for each mode is assigned to the network to further understand the travel patterns between OD pairs. Car and plane do not have their own network, as it is assumed that direct trips are possible between origin and destination. The rail network instead is a set of nodes and edges modelled to accommodate traffic.

Capacity on rail lines is a key factor when distributing demand across the network. Its assessment often requires granular data about local traffic patterns, operational and technological constraints, train frequencies, station layouts, signaling systems, and rolling stock types. These variables can vary significantly across regions and might not be accurately estimable for all proposed HSR lines. Given the "high-level" scope of this work to estimate benefits and costs and gain insight into the network's overall economic viability and strategic development, it is assumed that the infrastructure is not subject to capacity constraints.

Therefore, the potential trips between cities, translated into rail journeys trough the modal split, are assigned based on the shortest path available between OD pairs. An All-or-Nothing (AoN) approach is used, which assigns all the traffic related to one OD pair to the same path. This simplified representation is chosen mainly because of computational reasons. Potential drawbacks of this approach include the aggregation of traffic around centre of gravities, instead of a more even demand distribution, potentially reducing the feasibility of secondary lines. The end of the base network construction completes the data collection part of the first two Sections of the model. The built data sets are now inputted in the last iterative network growth Section, which will iteratively evaluate and invest in high-speed rail links and model the HSR network growth strategies.

3.5 Iterative Growth Module

In the previous Sections, the Input Data and the Base Network have been initialized. The former generating the necessary specifications for the HSR infrastructure as well as for the MACRO and MICRO layer grids, the latter enhancing the MACRO layer in terms of travel times and utilities calculations. Section 3.5.1 explains how the links are turned into corridors, Section 3.5.2 presents the candidate investment evaluation, while Section 3.5.3 introduces the financial feasibility calculations. Once the investment score is obtained, Section 3.5.4 explains how the investment decision is taken and finally Section 3.5.5 introduces how the network is updated and the iterative process can start again.

The third and last step of the proposed methodology aims at evaluating the potential HSR lines based on their performance within the given network structure. This is achieved through an iterative network growth model, which takes sequential investment decisions by weighting the performance of the new infrastructure against its costs. Figure 11 graphically shows the model structure, highlighting in red the evaluation Section, in yellow the financial feasibility Section, in green the investment step and in blue the model update phase.

In general terms, the iterative network growth Section receives the base network as well as the potential HSR links as input. It then simulates all the potential links, by individually adding them to the base network, and assessing their performance in terms of travel time and externality savings (Red Section). These benefits are then weighted against the costs of the infrastructure, obtained in Section 3.3.3, returning the Net Present Value (NPV) and the Benefit-Cost ratio (BCR), which evaluate the economical feasibility of such investment (Yellow Section). Based on budget availability, the link with highest scoring BCR is then built, by substituting the old travel time of the link invested, with a new and shorter HSR travel time (Green Section). Travel utilities and mode choices are updated as well, while the link is subtracted from the potential investments (Blue Section). Finally, a new updated base network is obtained, and the iteration can start again. In the next Sections these steps are explained in more detail.

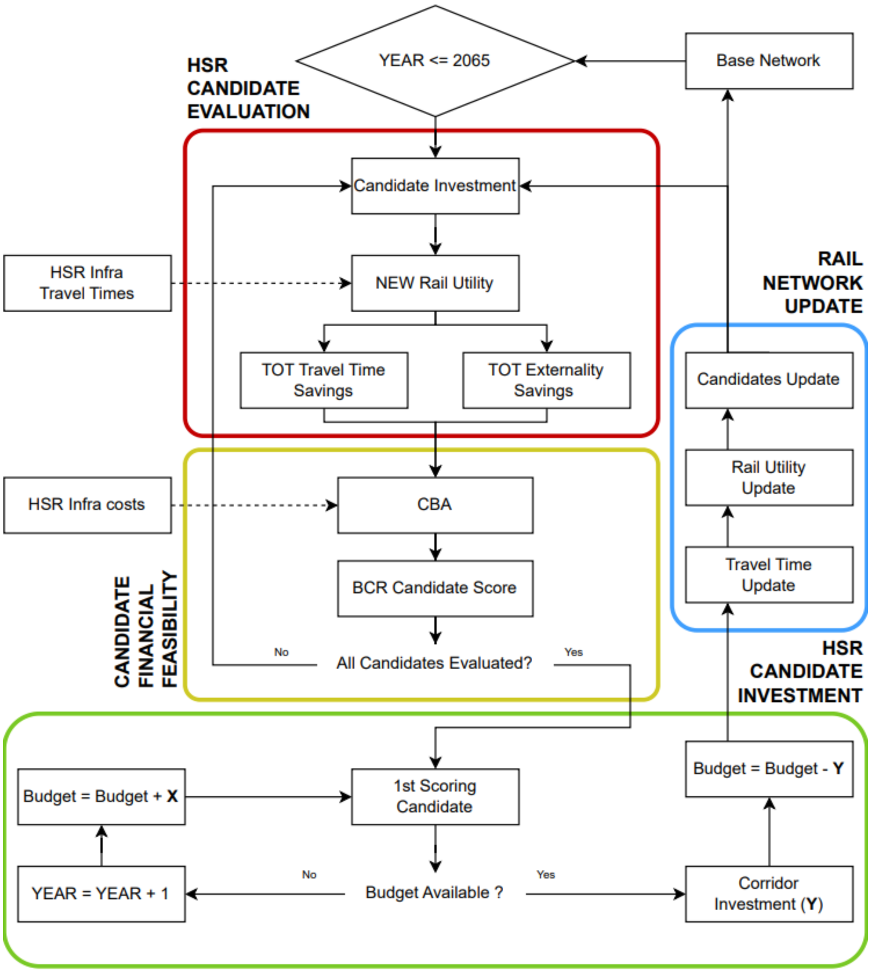


Figure 11 - Iterative growth module

3.5.1 The Construction of Corridors

As explained in the Input Data Section, each city can connect with other cities based on its influence. The latter determines the length of the distance radius of the circle area containing potential hubs. Figure 12 shows an example of the connection possibilities of a very influential city (blue dot on the left), and the more constrained link options for a less influential city (blue dot on the right).

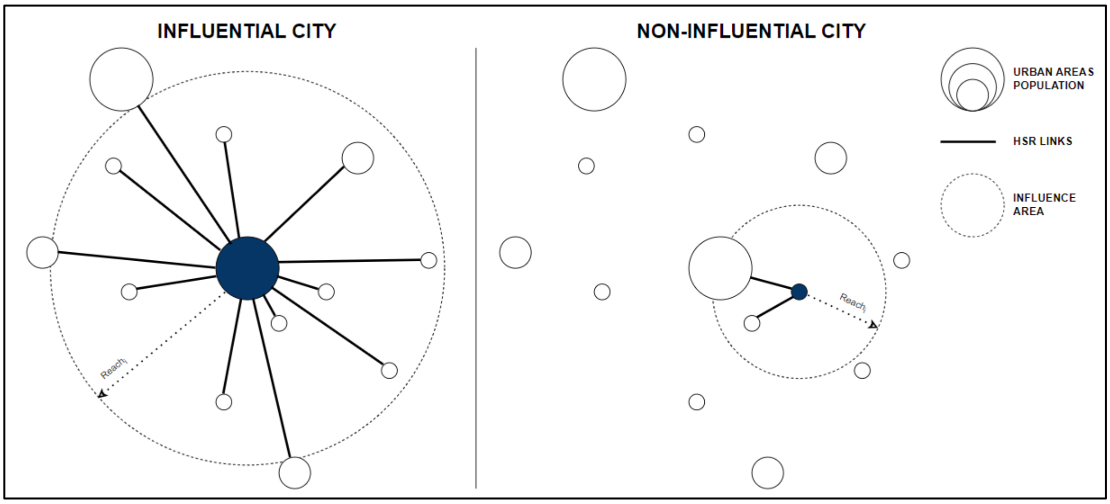


Figure 12 - The connection capabilities of influential cities (left) vs. less influential cities (right)

These links are crucial as they represent the rail connections of a city with its surrounding neighbours and determine the demand attracted to rail based on their performance. Within the iterative modelling phase, the decision is taken to expand these links into corridors, defined as a combination of links from an origin to a destination, as can be seen in Figure 13. This is done by using the k shortest paths method, which is a variation of the shortest path routing problem. Firstly, a link is taken, with its origin node and its destination. Then, the algorithm examines the k alternatives routes between this OD pair, by considering other edge combinations that form alternative paths to the original link. Given that the potential alternatives to a link are directly proportional to its travel time, k is used as a multiplier. Therefore, the number of alternatives is the result of k multiplied by the travel time of the considered link. These alternative paths are then examined and scored based on travel time. To further constrain the number of alternatives, the ones having a rail travel time exceeding a certain threshold (TT_k) are eliminated. The latter is obtained by multiplying the link's travel time by a predefined factor. The remaining pool of travel alternatives, including the original link, are added to the data set containing all potential candidate investments. Figure 13 shows the outcomes of this process for a big influential city.

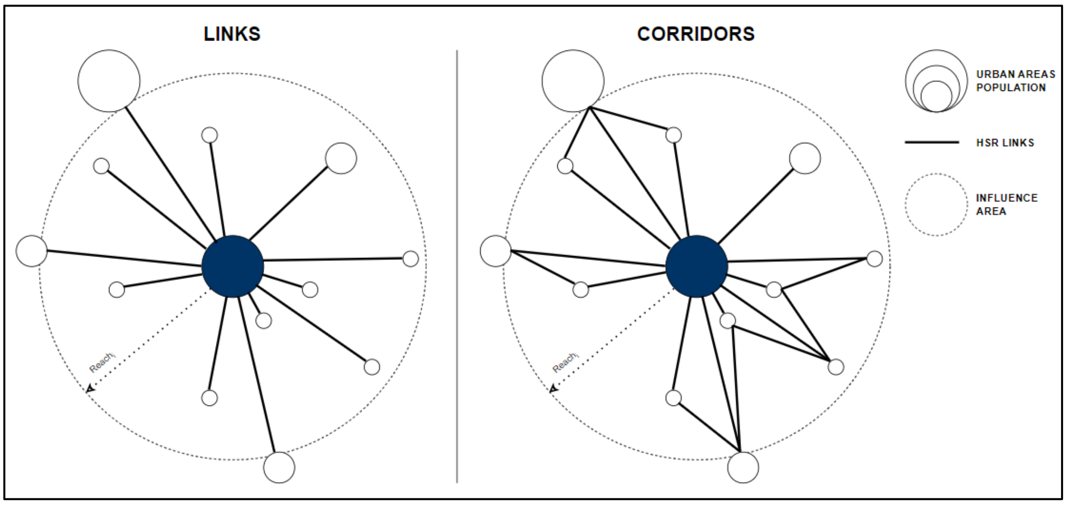


Figure 13 - The connecting links of a high influence cities transformed into corridors

The construction of corridors is necessary to increase the accuracy of the infrastructure modelling, by incorporating also smaller cities and evaluate different path alternative between two cities linked with each other. This allows the model to evaluate the interaction between the demand distribution and different infrastructural designs, but also to have a bigger utility forecast capacity by evaluating more links together as part of a bigger investment. In other words, if only the links are considered, the model does not have the ability to estimate the potential of high-speed rail connections over long distances. Imagine a node which has two connection options: one to a close and small city, and one to a bigger one located more in the distance. The latter connection would be more beneficial, as it would reduce the travel time for a higher number of people, while at the same time excluding the small city from the path. With the corridor set up, a further connection option is added: connecting the big city by passing through the smaller one. The slight increase in travel time, given that the path becomes longer, could be justified by the benefits of additional demand from the small city that would be connected to the HSR infrastructure.

Without transforming the links into corridors, sub optimal network evaluations may be obtained and the potential network effects not included in the evaluation process. By carefully calibrating the number of alternatives k and setting an appropriate time threshold TT_k, it is possible to improve the model's evaluation capabilities over longer distances. Finally, the resulting corridors receive their specifications in terms of travel time, investment costs and path, by combining all the single values of the links that create a corridor. The corridors are then added, together with the single links, to the pool of candidate investments.

Note that, together with TT_k and k, also the cities influence radius ($Reach_i$) plays a crucial role in the corridor creation process. A link that connects two cities over longer distances, on average generate a bigger set of alternative paths. As stated in Section 3.3.2 (II), this underlines the importance of the influence radius of each city, which determines to what extend the model can evaluate the performance of the HSR infrastructure. A bigger radius allows to evaluate demand shifts over larger spatial horizons and include more demand, while increasing the number of links and computational complexity.

3.5.2 Candidate Investments Evaluation

The set of candidate investments is obtained by combining rail links and rail corridors. In the first stage of the iterative network growth model, all candidate investments are thus evaluated to assess their transport performance based on how much passenger demand they attract thanks to the improved travel times. The latter can be divided between existing travel demand, calculated in the trip generation, and induced demand, people that start to travel given the change in the transport offer. In this thesis only the firs type of demand is considered, as induced demand is difficult to estimate and depends on multiple factors not included in this study, such as ticket price changes, frequency offered and comfort improvements.

The evaluation process consists in initializing the rail Sections targeted by the candidate investment with the new HSR travel times within the base network. Subsequently, their impact on the demand is assessed in terms of monetary weighted travel time and externality savings. The former is defined as the willingness to pay for a unit of travel time savings, usually considered as an hour. The latter are defined as the negative effects generated by transport as unintended impacts affecting the surrounding environment and all parties not directly involved into transport. The modelling process is schematically reported:

1. Each candidate investment is individually evaluated by initializing all the edges along its path with improved high-speed rail travel times.
2. The weighted shortest path is computed for all OD pairs in the case study. The new weighted rail utility is obtained for all OD pairs. Note, not all OD pairs will witness utility changes, as the new rail travel time will have a limited effect within their influence area
3. The mode choice is performed based on the new weighted utilities, obtaining the number of travellers affected by the new investment.
4. The monetary weighted travel time savings are calculated for each OD pair as the difference in weighted utilities multiplied by the number of passengers affected. Note that if plane utility is higher than the new rail one, the travel time savings will be negative and therefore subtracted from the total
5. Externality savings are calculated for each OD pair as the difference between the external impacts of other modes when compared to rail. Eventually, passenger leaving planes and cars are accountable for the externalities of the HSR. It is finally assumed that passenger switching over from conventional rail will not contribute to any externality savings.

The evaluation is performed for all the candidate investments and returns the total benefits in terms of monetary travel time savings and externality savings for each option. These values serve then as input for the next phase, financial feasibility.

3.5.3 Financial Feasibility

The second step of the iterative growth model translates the benefits and costs generated by each candidate investments into monetary values and calculates both the Net Present Value (NPV) and the Benefit-Cost ratio (BCR) for each potential candidate. This thesis assumes that travel time savings and externality savings are the two only sources of benefit.

I Travel Time Savings

To translate travel time savings into monetary values, the value of Time (VOT) is used. When considering a broad geographical which includes multiple countries, varying levels of economic development, income, and cost of living must be considered. Using a single national VOT might not accurately capture the diverse preferences and willingness to pay for time savings. Furthermore, adopting one single VOT value would not be in line with the country specific infrastructural costs calculations, leading to a misalignment in the appraisal process. Accounting for national attributes for both benefits and costs provides a more accurate representation of the investment framework and appraisal process.

These variations are captured by the differences in purchasing power between countries, expressed by the Price Level Index (PLI_c). The latter is obtained by dividing the Purchasing Power Parities (PPPs) by the current nominal exchange rate (Eurostat, 2019). Therefore, the ratio between the country specific index (PLI_c) and the mean of the case study ($\overline{PLI}$), provides an indicator of the magnitude of price levels in relation to other countries. The latter ratio is then multiplied by the average value of time ($VOT_{REFERENCE}$), returning the national monetary value of time (VOT_c) associated to one hour of travel time saving given the price level of that country. The final VOT_c of each country c is obtained with Equation 21.

$$VOT_c = \frac{PLI_c}{\overline{PLI}} * VOT_{REFERENCE}$$

Equation 21 - Value of Time as obtained for each country based on price level differences

After having defined country specific VOTs, these are multiplied with the weight parameters of Section 3.4.1 to obtain the final monetary value for the different trip stages. The sum of the monetized time parameters defines the total monetary travel time savings. Note that if a trip is performed between two countries, the VOT used is the average between the national ones. weighted to match the utility perception that travellers have of the different stages of a trip.

II Externality Savings

On the other hand, external costs of transport refer to the difference between the social and the private cost of transport, and are usually considered to be air pollution, climate change, accidents, noise, and congestion costs (European Commission, 2019). By internalising these costs, externalities are made part of the decision-making process of transport users. This can be done through regulation (i.e., command and control measures) or by providing the right incentives to travellers, namely with market-based instruments (e.g., taxes, charges, emission trading).

In this thesis externalities are not included in the cost of the single transport users but used in the appraisal of HSR infrastructural investments as a benefit component based on the shift of passengers to modes generating fewer externalities. The categories of externalities considered are taken from Grolle (2020) and monetized as euro per kilometre travelled. It is assumed that conventional and high-speed rail generate the same negative externalities.

The VOT and the externalities savings provide a monetary estimation of the benefits of a candidate HSR infrastructure, based on the impact it has on the choices of travellers. These benefits are considered to occur yearly and maintain a static nature over the operational lifetime of the infrastructure.

III Appraisal process

The second phase of the iterative growth model is responsible to calculate the financial feasibility of each candidate investment, by assessing to which extend the benefits of building the proposed HSR line can justify the costs over a specific over the operational lifetime of the infrastructure.

There are many methods that can be applied for project appraisal, as the Multi Criteria Analysis (MCA), the Cost-Benefit Analysis (CBA), the Cost-Effectiveness or Social Welfare analysis, as well as Risk Analysis (Rouhani, 2019). These methodologies can be used depending on the requirements of the appraisal and are often combined for a complete understanding of how a project scores, both socially and financially. For this thesis, given the data availability and its ease of use across a broad case study, the CBA analysis is chosen, providing a good trade-off between simplicity and data requirements. It allows to obtain the project's societal value by comparing costs and benefits in monetary terms, finally calculating the NPV of the investment.

The strategy adopted to deploy this tool, considers cashflow (CF_{year}) based on yearly benefits and cost occurrences, which are then discounted over a specific timeline at a certain discount rate (DR). Finally, the NPV is returned as the difference between the Net Present Benefits and the Net Present Costs. Furthermore, the BCR is obtained as the ratio between the former and the latter.

How benefits are obtained has been explained in the previous two sub-Sections, while the infrastructural cost formulation has been already explained in Section 3.3.3. Additionally, during the iterative process corridors might have been partially built. Therefore the $Built_{LINK}$ matrix keeps truck of the infrastructural evolution throughout the network, marking with 0 not existing links and with 1 existing links. This allows to remove the cost of existing infrastructure (C_{LINK}) from partially built corridors and obtain the total investment need (C_{INFRA}), as shown in Equation 22.

$$C_{INFRA} = \sum_{LINK=1}^{TOT\ LINK} (C_{LINK} * (1 - Built_{LINK}))$$

Equation 22 – Final infrastructural costs: Potential infrastructure minus existing infrastructure

The obtained infrastructural cost is further divided into planning costs and construction costs, to map the development of the HSR infrastructure in detail. For the former, the investment allocated is substantially lower than for the latter, as it covers mainly the analysis costs. This is modelled within the cashflow by defining average planning (T_P) and construction (T_C) times, and yearly planning ($C_{P_{year}}$) and construction ($C_{C_{year}}$) costs. Both the former and the latter are shares of the total investment, defined by

w_P for planning and by $1 - w_P$ for construction. Equation 23 and 24 present the calculations for the cost values in the two different stages.

$$C_{P_{year}} = \frac{w_P * C_{INFRA}}{T_P}$$

Equation 23 -Yearly planning costs calculation

$$C_{C_{year}} = \frac{(1 - w_P) * C_{INFRA}}{T_C}$$

Equation 24 - Yearly construction costs calculation

Once the infrastructure is ready, the cash flow still incurs into costs, defined as yearly maintenance expenses (M_{year}). These are a share (w_M) of the total investment (C_{INFRA}) over the operational lifetime of the infrastructure (T_{INFRA}) and calculated as shown by Equation 25. By relating maintenance costs to the total investment, it is possible to adapt the calculation to country specific values, as it has been done for infrastructural costs (Section 3.3.1).

$$M_{year} = \frac{w_M * C_{INFRA}}{T_{INFRA}}$$

Equation 25 - Yearly maintenance costs calculation

Finally, the yearly cashflow (CF_{year}) can be calculated. The latter can be of three types, depending on the timeline considered. In the first years within T_P, only planning costs are considered ($C_{P_{year}}$). From the end of T_P and within the construction years T_C, only construction costs ($C_{C_{year}}$) are included in the cashflow. Subsequently, once the line is in operation, from the end of T_C and within T_{INFRA}, yearly monetary travel time savings (TTS), yearly monetary externality savings ($EXTS$) and maintenance costs (M_{YEAR}) are included in the calculations. Equation 26 provides an overview of the mathematical formulation for the three types of yearly cash flow.

$$CF_{year} = \begin{cases} if\ year < T_P : CF_{year} = \ -C_{P_{year}} \\ if\ T_P < year < T_C :\ CF_{year} = \ -C_{C_{year}} \\ if\ T_C < year < T_{INFRA} :\ CF_{year} = \ TTS + EXTS - M_{year} \end{cases}$$

Equation 26 - Yearly cash calculations in relation to the operational timeline of the infrastructure

After the cashflow is obtained, it is possible to discount it using the discount rate (DR) over the considered timeline and calculate both the NPV and the BCR. Common appraisal practices found in literature use NPV to rank mutually exclusive projects, whereas BCR is preferred when choosing among unrelated alternatives in a budget constraint environment (Queensland Government, 2011).

The modelling framework is aligned with these considerations, as for each OD pair there are multiple mutually exclusive options, and the final investment choice is performed in a budget constraint scenario. The two decision criteria are thus used together, by ranking investment for the same OD pair based on the NPV and taking the final investment decision based on the BCR.

Furthermore, combining BCR and NPV allows to formulate national specific infrastructural costs and VOTs without having biased results during the appraisal process. If for example only NPV would be used to rank investments, projects in countries with higher VOTs would always score higher, as the difference between Net Present benefits and Net Present Costs would yield more returns than in countries with low VOTs. BCR avoids this by calculating the ratio between the two. In this way high VOTs (i.e., benefits) are balanced by higher costs or the opposite, thus the results for all countries are on the same scale.

The final set of candidate investments contains one infrastructural option per OD, which are ranked based on their BCRs.

3.5.4 Investment Decision

Once the set of candidate investments has been obtained, the best scoring one in terms of BCR is chosen. This is the HSR connection that generates the most utility at that specific iteration, because of the dynamic interaction between passenger demand and infrastructural supply. If none of the candidate investments has a BCR higher or equal than 1, the iterative process stops, and no further investments are carried out.

Subsequently, once the best scoring candidate investment is identified, the model must comply with its budgetary constraints for that time step before proceeding into investing. The yearly available budget is obtained by summing the yearly budget contributions that each country makes to the common budget. This is in line with the assumption of a centrally coordinated decision making process (Section 3.2). National contribution amounts are obtained as a share of national GDP. This share ($\%GDP$) is calculated on historical data of countries that already have HSR infrastructures, by analysing how much has been spent yearly since the first line came into operation as a portion of each country's GDP ($GDP_{COUNTRY}$). The total yearly budget ($Budget_{YEAR}$) is thus obtained as shown in Equation 27.

$$Budget_{YEAR} = \sum_{COUNTRY=1}^{TOT\ COUNTRY} \%GDP * GDP_{COUNTRY}$$

Equation 27 - Yearly budget as a summation of all the countries contribution in terms of GDP share

Note that countries contribute to a common budget, therefore if a nation contributes with a certain amount, this money is not automatically reinvested in the origin country, unless it is the location of the best performing investment option.

There are two different situations when it comes to allocate investments. Firstly, the costs of the best performing option are checked against the yearly budget. If enough budget is available, the investment is carried out. If the budget is not enough, no investment is carried out for that year, and the model saves the money and moves to the next time step (Year+1). By doing so, an additional yearly budget amount is added to the previous savings, therefore doubling the investment budget available. Costs of the best scoring option are then once again checked against the budget and if enough money is now available, the investment can take place. Note that once an investment has been carried out and there is budget left, the model can revaluate other potential candidate links and perform multiple investments in one year.

Once an investment is performed, although construction time is considered before the activation of the line, the edges are immediately initialized with the improved travel time. This is done to account for planned infrastructure when evaluating potential HSR connections in the following iterations. In modelling terms this means that the base network is immediately updated, as explained in the next Section.

3.5.5 Network Update

The last block of the iterative network growth model is responsible for updating the base network and the dynamic data sets of travel utility, mode choice and candidate investments. This update process is carried out all at once and happens every time an investment is performed.

Firstly, the built option is removed from the pool of potential investments. In this way it can not be considered and evaluated again. Given the number of links composing the investment, all OD pairs corresponding to each Section are removed. Furthermore, investments that are partially built are eliminated. This has a positive effect during the iterations in terms of computational time.

The rail links that are part of the investment are now considered active and are marked with 1 in the existing infrastructure matrix $(Built_{LINK})$. This is a crucial step because it affects the costs of future potential investments that include some of these links.

Travel time is updated for the connections that have been built, by including the new high-speed rail parameters. Subsequently, mode share is computed again for the whole case study.

Finally, the yearly budget is updated by subtracting the investment costs of the new investment. If budget is left but no other investments are carried out, it is saved for the next iteration.

This concludes the iterative modelling procedures. The next Section introduces the case study to which these modelling techniques are going to be applied, tested, and studied.

04

Case Study

Copenhagen to Malmo Oresund Bridge inaugurated in 2000
Denmark and Sweden

4 Case Study

In this chapter, the case study to which the methodology is going to be applied, is introduced. Section 4.1 presents the general scope, Section 4.2 the time scope, Section 4.3 concentrates on the geographical scope, while Section 4.5 presents the setting of the model's parameters. Finally, the three modules of the methodology are presented under the case study implications, with the specific data sets for the Input Data Module in Section 4.5, the modes specifications and network configurations for the Base Network Module in Section 4.6, and lastly the case study components of the network expansion for the Iterative Growth Module in Section 4.7.

4.1 General Scope

This thesis focuses on the HSR infrastructure of the European continent, by considering the long-distance European transport market. UIC defines HSR lines to be rail infrastructures capable of services with speeds equal or above 250 km/h. Furthermore, for connections where no air competition is available, this speed can be lowered to 230-220 km/h or at least above 200 km/h, given that this is enough to catch as many market shares as a collective mode of transport can do (UIC, 2018). Nevertheless, two bottom lines are assumed when modelling high-speed rail infrastructures: These must be dedicated passenger lines and the average speed assumed is 220 km/h. The latter has been obtained by Donners (2016) through regression analysis of 30 existing and 30 modelled HSR lines in Europe.

4.2 Time Scope

The timeline considered, within which the investments are carried out and the infrastructure constructed, starts in 2023 and finishes in 2065. The timeline is formulated to include the European Union's milestones for 2030 and 2050 (European Commission, 2020a), and to additionally account for 15 years of average construction time (European Court of Auditors, 2018). Thus, the investments are carried out between 2023 and 2050, while the construction work and the benefits of the lines will take place between 2038 and 2065. On the other hand, all the data sets considered for the case study are based on 2019 available data. This allows to exclude the significant impact of the COVID-19 pandemic on both the transport and the socio-economical statistics.

4.3 Geographical Scope

Continental Europe is chosen as the geographical area for the case study, with a final selection of 28 countries. 25 belong to the European Union, excluding Malta and Cyprus. To these, Norway, Switzerland, and the United Kingdom are added due to of their socio-economical importance and geographical interconnectedness with the case study area. Figure 14 shows a comprehensive map of the geographical scope.

The countries considered in the case study present advantages that facilitate the application of the iterative network expansion model. Firstly, the European continent can be considered one of the world's leaders in HSR services, with a decade long history in technological and infrastructural development. Italy and France where among the first nations in the world to have a high-speed rail line, whereas Spain is currently the second country in the world by HSR network extension after China. The attention of European countries towards this mode of transport has also grown in the last years. These factors potentially increase the interest for such modelling techniques and applications.

Secondly, the geographical scope considered also allows studying the effects of rail development across borders and the potential outcomes of a common investment strategy shared by various nations. The main drive is one side the European Union facilitating the dialogue and the technical interoperability, but also the geographical vicinity and the sharing of a common "European" culture. Additionally, the European continent is characterised by intense economical interaction (Bouley, 1986), which means consistent flows of people and goods across borders, especially within the Schengen Area, which grants the freedom to move to more than 400 million people. Furthermore, the European continent presents big differences in terms of population density and topographical features. These factors create an interesting case to evaluate the behaviour of the model in relation to transport demand, cross-border connections, and terrain characteristics.

Figure 14 - Geographical scope of the case stud. European Union in green extra-EU countries in brown

Many countries in the continent do not have any HSR infrastructure, and the European Union has grand plans to expand the network in the future. This means that a good amount of data is also available to predict future infrastructure and to compare the model outcomes with current policies. This is facilitated especially by the consistent data gathering among European nations and within the European Union. Most of the available information is up to date and accurate, crucial to generate accurate predictions of future scenarios. Finally, Table 7 summarizes all the countries included in the case study area.

Table 7 - Countries select in the geographical scope

Countries			
Austria	Finland	Latvia	Romania
Belgium	France	Lithuania	Slovakia
Bulgaria	Germany	Luxembourg	Slovenia
Croatia	Greece	Netherlands	Spain
Czech Republic	Hungary	Norway	Sweden
Denmark	Ireland	Poland	Switzerland
Estonia	Italy	Portugal	United Kingdom

In modelling terms, the case stud area is represented through a geographical perimeter, as shown in Figure 15.

Figure 15 - Geographical perimeter of the European continent, visual representation

The geographical permitter is then translated into coordinates in the decimal degree format. For the scope of this research the values of Table 8 are used.

Table 8 - Geographical perimeter of the European continent with coordinates

Coordinates	
Latitude North	$71.30\,°$
Longitude West	$-11\,°$
Latitude South	$32\,°$
Longitude East	$34.5\,°$

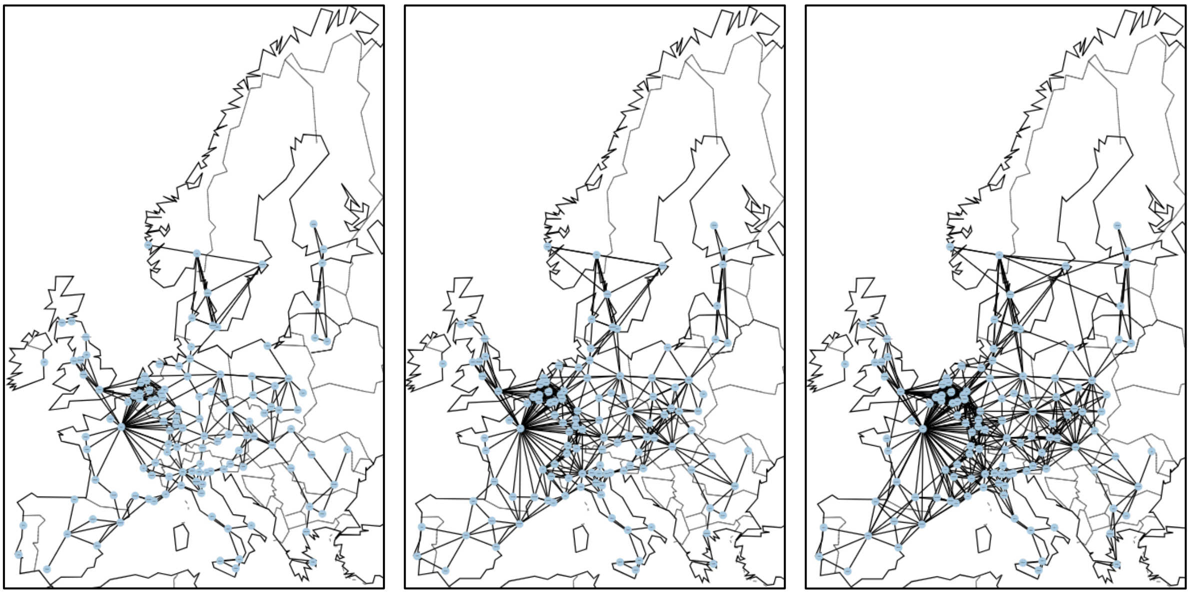
A subset of attributes is modelled for each country, to grasp the differences across national borders within the modelling. These include the national population, the national languages spoken, the belonging of a country to the Schengen area, the country's surface, and the urbanization ratio, obtained as the share of population living in cities. Additionally, three other indicators are modelled for calculating the infrastructural costs. Firstly, the country's density, in terms of the total population per square kilometre, the terrain coverage, defined as the percentage of mountainous terrain (EEA, 2019), and the Price Level Index (PLI), obtained from Eurostat (2019), which accounts for the different purchasing powers and thus price indices of each country.

4.4 Parameter Setting

The model includes several parameters that are calibrated within the case study and affect the model's outcomes. These parameters are the k shortest path and TT_k time limit for the creation of corridors presented in Section 3.5.1, as well as the link creation distance parameter d presented in Section 3.3.2.

4.4.1 d: Distance Influence of a City

Distance parameter d is part of the influence area formula which determines the distance range used to establish connections with neighbouring cities. This value is multiplied by the influence weight of each city, obtained from the relationship between population, economical output, and population density, as explained in Equation 6 of Section 3.3.2. Parameter d has a significant impact on computational time, affecting the number of connections and in turn the number of corridors and links to be iteratively evaluated. After an initial definition of the parameter's magnitude, expressed in tens of kilometres, d is iteratively tested over a certain distance range between 100 km and 150 km by adding 10 km at each iteration. Figure 16 shows the three distinct distance cases considered.


(a) d = 100km

(b) d=130km

(c) d = 150km

Figure 16 – Distance d parameter setting

Based on the calibration process, 130 km is chosen as distance parameter, presenting a trade-off between establishing a continues connection grid between all cities while at the same time maintaining feasible model run times given the computational power available. The final set of links amounts to 450 feasible connections between cities.

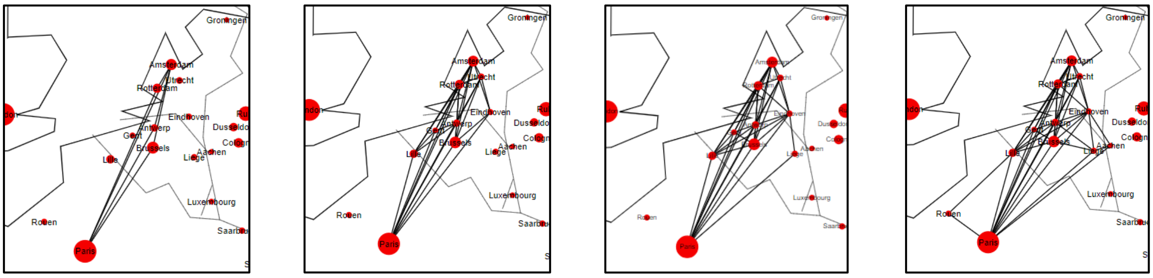
4.4.2 k & $time\_limit$: Number of Shortest path Alternatives

These two parameters are calibrated together as they are interdependent when it comes to corridor creation. Both set upper bounds to the number of alternative paths that the model is allowed to evaluate, in terms of number of alternatives and travel time increase of the alternatives. Higher values for k do not necessary increase the path alternatives, as they are bound by TT_k, and vice versa.

To obtain the upper bounds, both k and TT_k are multiplied by the connection's travel times, so to generate several alternatives directly proportional to the HSR distance between cities. This allows to incorporate the connection characteristics within the creation process, generating a pool of alternatives tailored around the specific OD pair.

As for parameter d, these parameters also have a significant influence on computational times. A larger number of path alternatives increase evaluation times, whereas low values of k or TT_k decrease the accuracy of corridor creation. For this thesis, both parameters are calibrated in a way to reproduce all existing HSR infrastructures in the case study, while minimizing the number of alternative paths. The upper bounds are found with the Amsterdam to Paris high-speed rail connection, which presents the highest number of iterative alternative paths generation, before the existing HSR link combination is achieved (i.e., Amsterdam-Rotterdam-Antwerpen-Bruxelles-Lille-Paris). The final value obtained are thus k equal to 20 and TT_k equal to 1.3, as shown in Figure 17.

k calibration



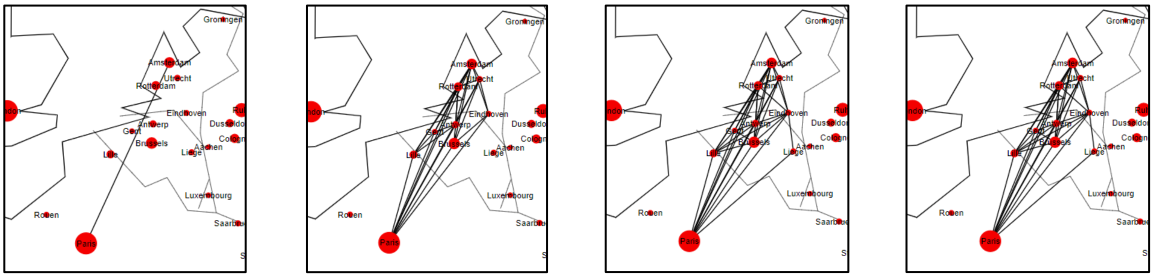
K = 1, TT = 1.3
Corridors = 4

K = 10, TT = 1.3
Corridors = 29

K = 20, TT = 1.3,
Corridors = 58

K = 40, TT = 1.3
Corridors = 141

$time\_limit$ calibration



K = 20, TT = 1
Corridors = 1

K = 20, TT = 1.2
Corridors = 28

K = 20, TT = 1.4
Corridors = 58

K = 20, TT = 1.5
Corridors = 58

Figure 17 - k and time limit parameter setting

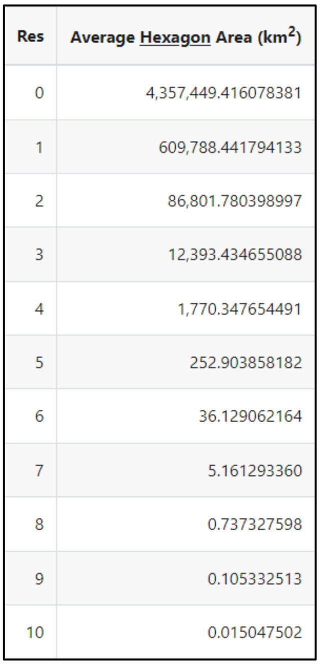
As can be seen in Figures 16 and 17, k has a bigger influence determining the number of alternatives in the corridor formation process than TT_k , especially in dense areas where there is a high number of combinations available.

4.5 Input Data Module Specifications

In this Section, the parameters considered within the case study related to the MICRO layer grid are presented in Section 4.5.1, the MACRO layer grid parameters in Section 4.5.2, and the HSR infrastructure parameters are presented in Section 4.5.3.

4.5.1 MICRO Grid

The MICRO layer grid is the three dimensional representations of the terrain, which is used to obtain the technical specifications regarding potential HSR infrastructures. To this end, Uber's H3 hexagonal hierarchical spatial indexing system is used, which allows to model each terrain point as a hexagon, whose centroid contains all the information regarding the area covered by the hexagonal shape. Based on the desired level of detail, hexagons can represent bigger or smaller portions of space. In Figure 18 the different resolution levels specifying different areas are shown. The higher the resolution, the more accurately the terrain can be modelled.



Res	Average Hexagon Area (km^2)
0	4,357,449.416078381
1	609,788.441794133
2	86,801.780398997
3	12,393.434655088
4	1,770.347654491
5	252.903858182
6	36.129062164
7	5.161293360
8	0.737327598
9	0.105332513
10	0.015047502

Figure 18 - Hexagon resolution and relative average square area

Resolution level number 6 is chosen for this thesis, as it is the best trade-off between accuracy and computational power available. Having obtained the area specifications, other measurement values of the hexagon can be calculated. One additional key parameter is the distance between the centroid of two hexagons, which can be obtained by calculating the greater circle distance between the two geographical points. The final distance is thus obtained to be 6 kilometres. Furthermore, the side (s) can be obtained with the formula for the hexagonal area ($\text{Area} = \frac{3\sqrt{3}*s^2}{2}$). The final dimensions used in this model are displayed in Figure 19.

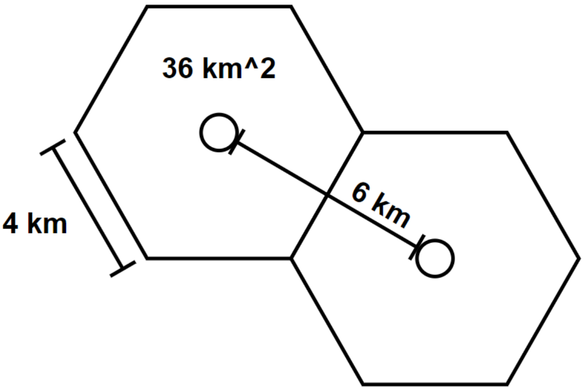


Figure 19 - Hexagon's dimensions

Subsequently the geographical boundaries are populated with the hexagons. This returns 353895 hexagons of 36 square kilometres, from which sea hexagons and the area of countries out of the scope are removed. The final number obtained is thus 145254 land hexagons. To visualize the H3 components, the CARTO (CARTO, 2023) visualization tool is used, with the first graphical impressions shown in Figure 20.

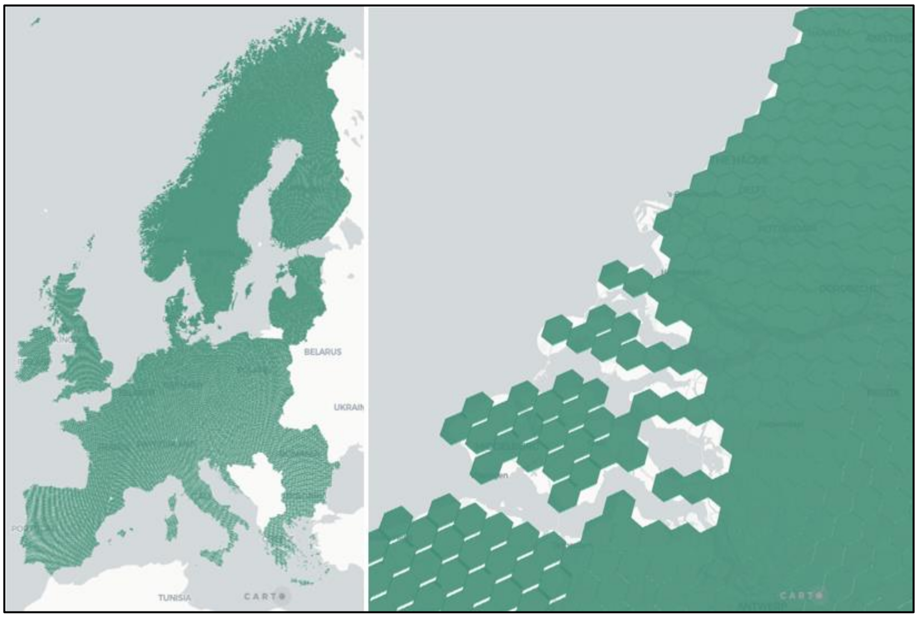


Figure 20 - Hexagonal subdivision of the case study area (left), and of the Rhine river delta (right)

Once the geographical space is properly referenced, each hexagon's neighbours are identified, to understand where edges can be built between hexagons. With the two-dimensional grid in place, a third dimension can be added. For this purpose, QGIS in combination with the Copernicus' DEM raster data set is used (Copernicus, 2023). After having retrieved the values and cleaned the data, Figure 21 shows the obtained results.

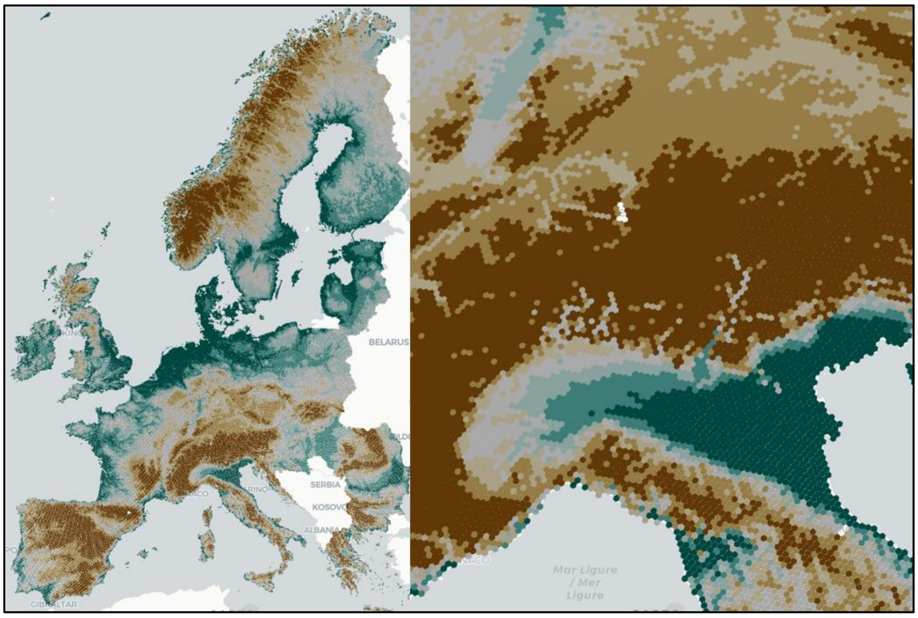


Figure 21 - Elevation profiles of the case study area (left), and of the central Alpine range (right)

Subsequently, each hexagon is individually layered into a series of parent nodes located at different elevation levels, as explained in Section 3.3.1. Thus, the hexagon's modelling potential is enhanced allowing to represent both surface and underground terrain, as well as three types of edges: Horizontal, diagonally upwards, and diagonally downwards. The steepness of the diagonal edges must be carefully assessed as it represents the inclination design parameter of potential HSR lines. The former is calculated as the elevation difference between layers divided by the previously defined 6 km distance between the centroids of the hexagons.

For dedicated HSR lines, the common gradient specified by UIC ranges between 3,5% and 4% (UIC, 2018). Thus, the final elevation difference between layers, with the proper rounding up, is calculated to be 250 meters, resulting in a 4% gradient for the diagonal edges of the MICRO layer grid. In this way, each hexagon is divided into layers 250 meters from the bottom up, resulting in a set of parent hexagons that have the same geographical location, but different terrain specifications and elevation depending on the level.

If, for example, a hexagon has a surface elevation of 378 meters, it is represented only by two centroids, one at 250 meters and the other at 378 meters. Oppositely, a hexagon with an elevation of 1178 meters, is composed by a set of 5 centroids, as shown in Figure 22. Therefore, the initial 145254 hexagons become 293258 centroid points, creating a three-dimensional grid.

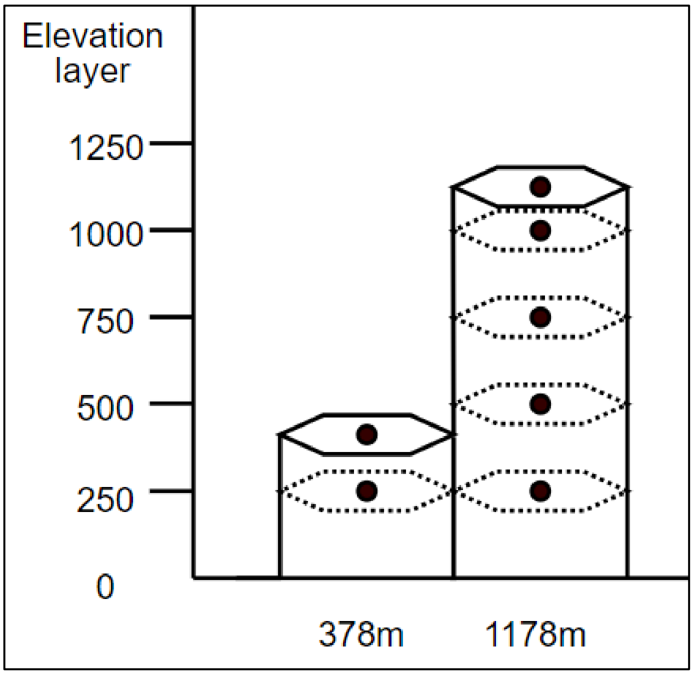


Figure 22 - Example of hexagon layering for two different elevation values

With the hexagon layering the terrain is discretized in three dimensions and elevation variations are modelled within 250 meters. To understand the implications of the terrain conformation on the infrastructural costs of future potential HSR lines, these variations are translated into monetary terms. This is done by assigning a cost weight to the hexagon's centroid based on the country of belonging and whether they represent an underground or surface layer, as explained in Section 3.3.1.

The process starts by identifying an average surface and underground HSR cost parameter for the whole case study. Defining these average parameters can done by retrieving values from the regression of historical data calculated by UIC (UNECE, 2022) as shown in Figure 23. Although the level of approximation is high, most of the results score within +/-25% of the average regression values. A good example of how project costs are country specific, is the HSL Zuid in the Netherlands, where high population densities and difficult geological conditions made the line very expensive. In Italy, the construction of high-speed infrastructure requires compensative measures such as bridges, roads, and noise protections. The United Kingdom also has high construction costs due to population density and land costs along its main north-south corridor.

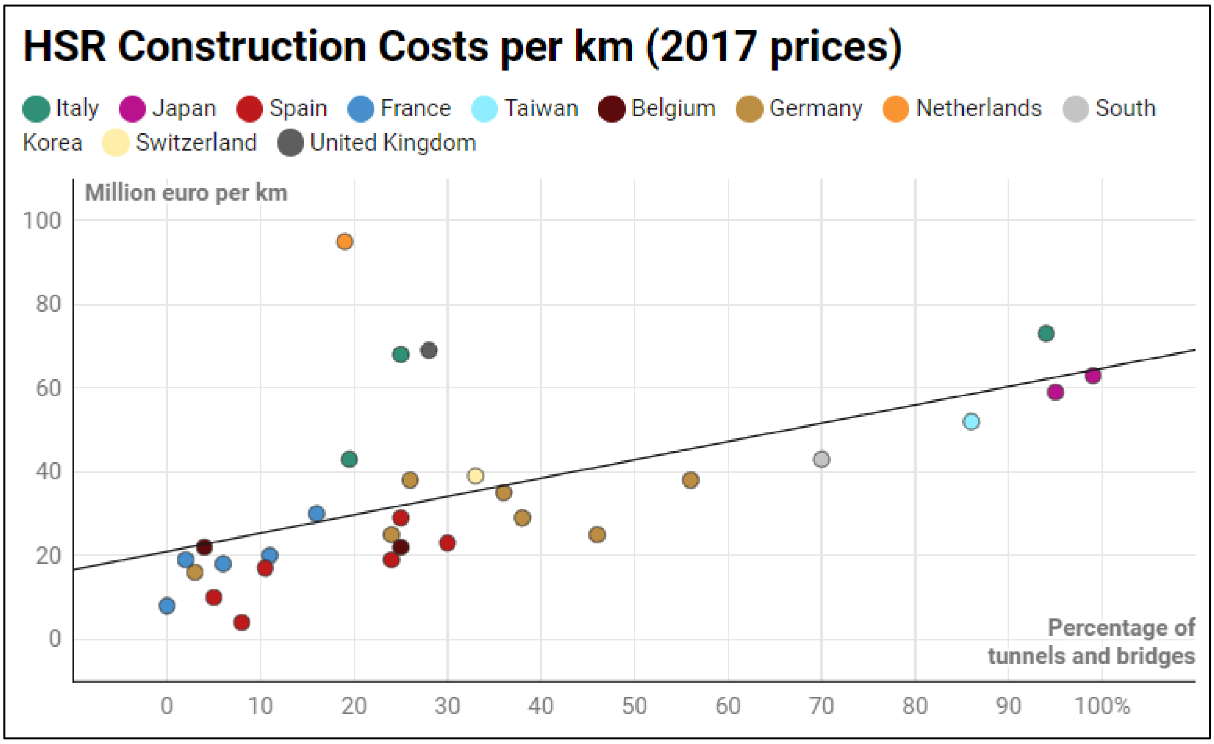


Figure 23 - "Efficiency in High-Speed rail – How to evaluate and how to achieve? UIC Workshop Operating High-Speed lines: in search of efficient solutions". Matthias Meyer, Deutsche Bahn. UIC Paris, 31 January 2019. From UNECE, 2022

Figure 23 shows the infrastructural cost for some of the major HSR projects to date. It is noticeable that the majority of the projects fall within the low-cost category with a low percentage of tunnels and bridges. This can be potentially attributed to the fact that big urban centres are rarely located in mountainous areas, that costly HSR infrastructures are less likely to receive funding if not strictly necessary, or that the high costs of HSR in rough terrains significantly favour alternative transport modes.

Therefore, for this thesis, the values of Table 8 are considered, which cover the majority of existing HSR lines and provide clear quantitative values for the cost estimation. The average costs within the case study are thus defined as 20 million euros per kilometre for surface infrastructure, and 60 million euros per kilometre for underground infrastructure. Excluding Japan, only the countries with the highest GDPs in the case study are shown, therefore average costs are adjusted to the average European level with the PLI, and then further adjusted for inflation to current values. Finally, Table 10 shows the average costs of construction obtained: 19 million euros per kilometre for surface and 55 million euros per underground infrastructure.

Table 9 - Average cost values per kilometre for surface and underground HSR infrastructure

$\overline{Cost\_pkm\_Surface}$	$\overline{Cost\_pkm\_Underground}$
19 million euro/pkm	55 million euro/pkm

These values can be considered in line with the cost estimations of the European Court of Auditors (2018), which established a single average cost per kilometre at 25 million euros by mainly auditing surface infrastructures. With the average cost values in place, these are adjusted for the single countries. The parameters considered for the adjustments are the ratios of mountain coverage, the national GPD, national PLI and the population density against the averages of the case study. The mean of these three returns the final cost weight for each country, as explained in Section 3.3.1 and reported in Figure 24.

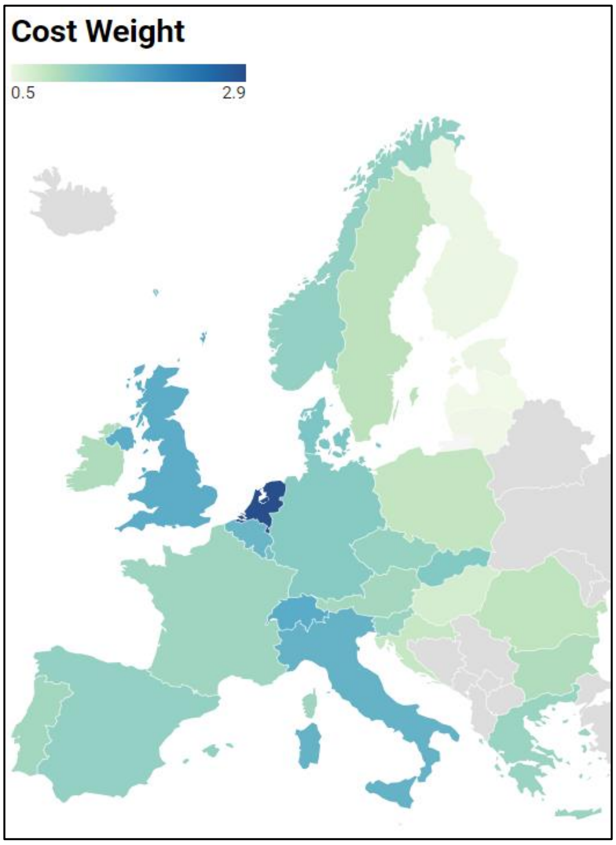


Figure 24 - Cost weights for each country of the case study

The final cost weight is then multiplied by the averages of surface and underground infrastructure, obtaining the final infrastructural costs per km for each single country of the case study. The final cost values for all countries can be found in Appendix C, whereas the validation of such parameter is reported in Appendix I.

In case of HSR sea infrastructure in the form of bridges or tunnels, the process is different. Given that these are even more unique constructions and that the number of potential connections considered for the case study is relatively low, the cost estimations are done manually. Specifically, 8 sea straits are chosen based on existing infrastructures, infrastructure under construction or planned. Table 10 lists each of the projects and their infrastructural specifications, as well as the cost per hexagons considered for the cost modelling process. The latter must be calculated separately as some sea links do not cover the entire length of a hexagon and must be averaged with extra land connections. The complete calculations can be found in Appendix C.

Table 10 - Sea infrastructures included in the case study

Name	Country Code	Infra Type	Status (2023)	Length (km)	Cost (2019 ml/km)	Hexagon Cost (2019 ml/km)
Stretto di Messina	IT	Bridge	Planned/In construction	3.5	1000	714
Channel strait	FR-UK	Tunnel	Operational	56	1650	294
Oresund strait	DK-SE	Bridge	Operational	16	5500	195
Fehmarn	DK-GE	Tunnel	In construction	19	6400	183
Little Belt strait	DK	Bridge	Operational	1.7	1900	141
Great belt strait	DK	Bridge	Operational	6.7	500	145
Storstrom strait	DK	Bridge	Operational	3.2	270	282
Gulf of Finland	FI-EE	Tunnel	Proposed	100	1500	143

This infrastructure is then paired with the corresponding sea hexagons that have been eliminated when filling the case study geographical area. Figure 25 shows a graphical example of the potential tunnel in the Gulf of Finland between Helsinki and Tallinn.

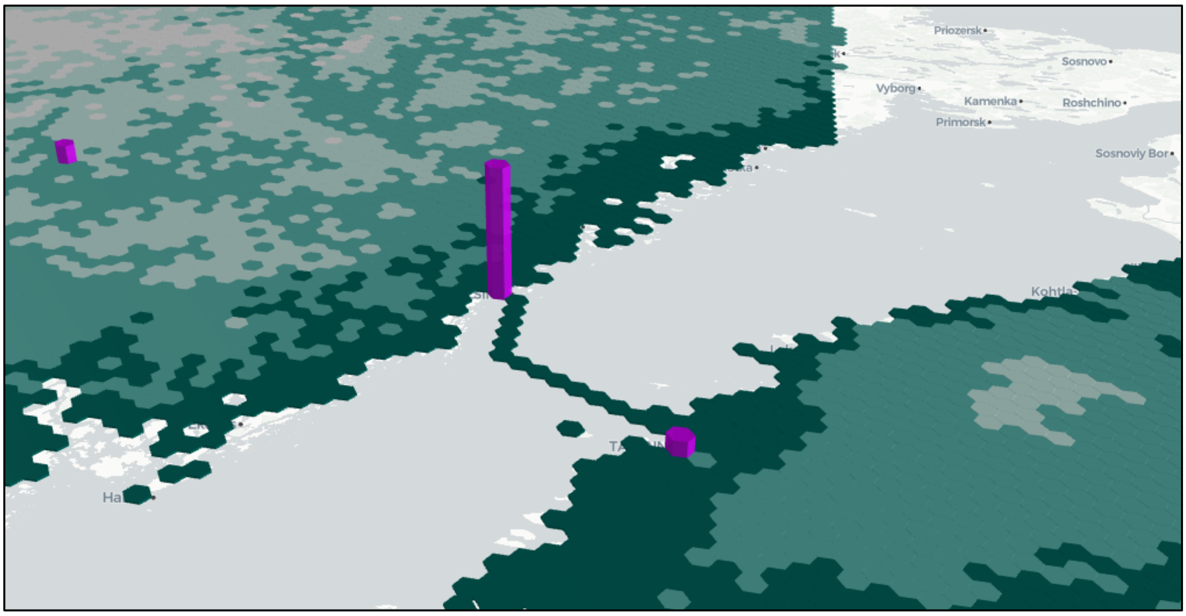


Figure 25 - Modelled sea infrastructure in the Gulf of Finland (Helsinki north, Tallin south)

With all the costs in place, the edges can be initialized. The assigned weight is obtained as the average of the costs of the centroids that the edge is linking. The edge between a surface and an underground node will therefore be the average between surface and underground infrastructural costs, simulating the entrance of a tunnel. For links crossing borders, the weight is calculated as the average between two different national values.

Finally, 1633783 edges are initialized to form an intricate network of horizontal, upgoing or down going infrastructural Section. The final three dimensional cost grid structure is now complete and can be used to model HSR infrastructures incorporating topographical features.

4.5.2 MACRO Grid

The MACRO layer grid models the population distribution across the case study and establishes the rail links between the nodes representing the urban hubs. The selection criteria for a hub to be considered is based on the methodology used by Donners (2016), who scored cities based on population, regional GDP and level of higher education. The author obtained a selection of 125 cities, including major urban centres and capitals of countries bordering the case study nations (e.g., Russia, Serbia, Ukraine). The latter are removed because outside the case study, and further 12 cities are added as being part of existing high-speed rail connections or being crucial logistical hubs for the model. Table 11 present an overview of the latter both types.

Table 11 - Additional urban hubs included in the case study

Cities belonging to existing HSR networks	Cities included for modelling purposes
Nuremberg	Timisoara
Erfurt	Malmo
Kaunas	Bern
Mediopadana (Reggio Emilia, Modena, Parma)	Salzburg
Trento	Trieste
Stretto (Reggio Calabria, Messina)	Graz

The addition of these nodes brings the final data set of cities again at 125. To be noted is the inclusion of Dublin in the case study, which given its importance is of primary consideration. But building HSR lines between the UK and Ireland is technically very challenging and no plans have been drafted so far. Therefore, the city is maintained within the case study but no alternative connections to plane are provided to connect Ireland to mainland UK or Europe.

The population of each city, which represents the demand input of the model, is obtained through the data available for FUA (Functional Urban Areas) areas within the European continent. These are defined by the OECD as the geographical space comprising “the inhabitants of the city and the surrounding areas (commuting zone) whose labour market is highly integrated with the city” (OECD, 2023). Including the wider commuting area of a city allows considering a bigger demand basin that could potentially commute to high-speed rail stations from the province, therefore mapping a larger percentage of the population more accurately.

The connections between cities are modelled by the MACRO network and represent the rail links available in the model, both for conventional and for HSR. The feasibility of these connections is based on the modelling approach of Section 3.3.3, which defines the influence range as proportional to the GDP per capita and the population, but disproportional to urban density. Therefore, each city receives a connection score based on the aforementioned factors. Figure 26 reports the results for each urban area by highlighting high connections scores in dark blue. Big cities have a significant connection potential, such as in the case for Paris, Madrid, and London. Instead, big cities in countries with a high number of urban centres in relation to surface have a lower connection score, such as Berlin, Amsterdam, and Brussels. Finally, it can be seen how medium-small cities in countries with fewer urban centres, have a high connection potential. This is the case of Stockholm, Oslo, Helsinki, and Bucharest.

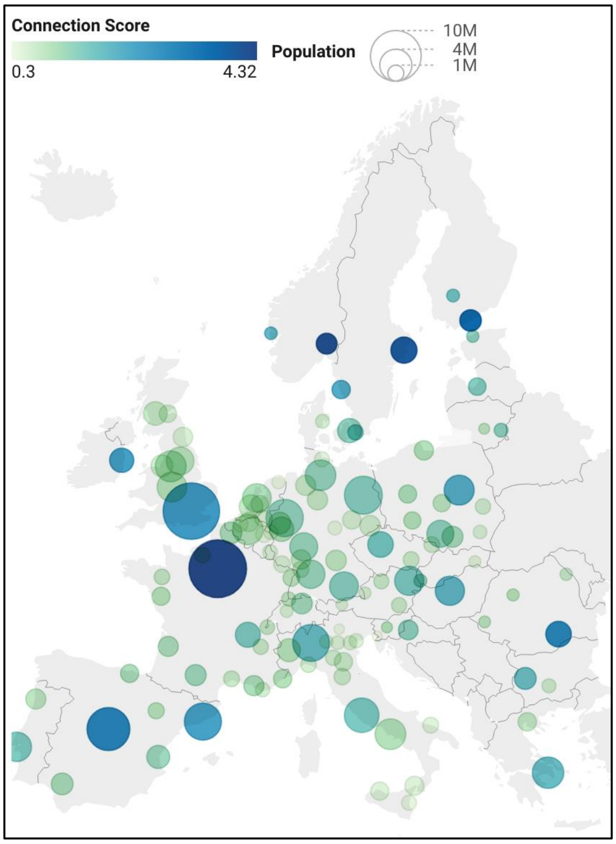


Figure 26 – Connection score, proportional to GDP per Capita and Population, disproportional to Urban Density

The connection score that each city receives is then multiplied by the distance parameter d of 130 kilometre set in Section 4.4.1. Finally, a total of 432 connections of various lengths are obtained. As for the cities, additional edges are provided for a more complete modelling of the urban hubs and connections. The latter can be divided between existing HSR infrastructure and potential edges with high logistical value for the model, as shown in Table 12.

Table 12 - Map of the rail links considered in the case study

Existing or planned HSR edges	Edges with high logistical value for the model
Innsbruck - Trento	Venice - Trieste
Erfurt - Nurnberg	Bremen - Groningen
Erfurt - Hannover	Kosice - Cluj-Napoca
Napoli - Bari	Vilnius - Tallinn
Stretto - Catania	Timisoara - Sofia
Palermo - Catania	Nantes - Bordeaux
Stretto - Palermo	Genova - Firenze
Stretto - Napoli	Berlin – Warsaw
Berlin – Munich	Berlin - Amsterdam

This brings the total rail links available to 450, as presented in Appendix D. The existing or planned HSR edges of Table 12, have not been obtained by the link creation methodology, mainly because there are smaller hubs missing in the case study which make it unfeasible. As for the edges included for modelling purposes, some form crucial transportation corridors (e.g., Innsbruck – Trento), others close gaps (e.g., Bremen – Groningen), while some edges must be manually modelled for countries with vast surfaces but low number of urban hubs (e.g., Romania, Finland).

Each edge is a rail link, modelled to accommodate conventional rail and upgradable to high-speed rail by incorporating the HSR parameters found with the MICRO network. The final map of the links considered is provided in Figure 27.

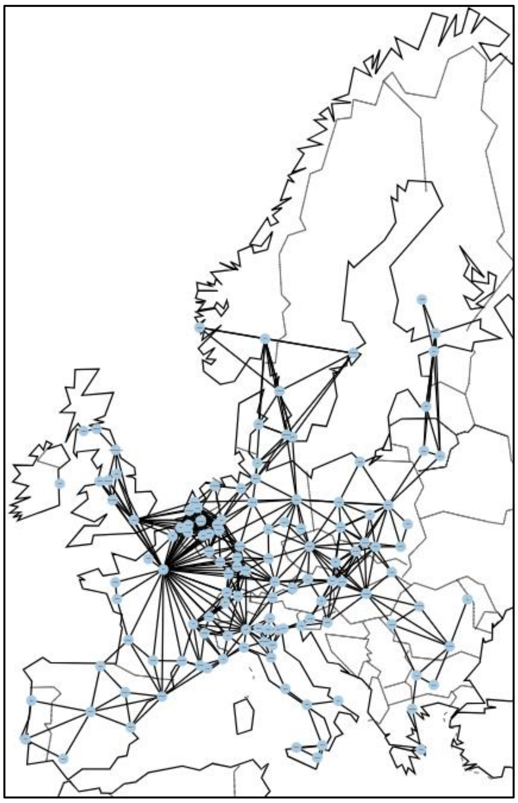


Figure 27 - Map of the 450 rail links considered in the case study for the MACRO grid

From Figure 27 it can be noted that the higher the influence of a city, the better and farther it connects with the cities around it. Paris is clearly the central hub for western Europe, whereas the Benelux is a dense interconnected network of lines. More to the East, the connections between Austria, Czeck Republic and Poland highlight good connection potential, as well along the imaginary line between Budapest and southern Germany.

The MACRO layer network obtained defines all the demand centres (i.e., cities) and the rail connections between them. This network is the guideline for the creation of the potential HSR links, as it defines the existing and potential rail connections available withing the case study.

4.5.3 High-Speed Rail Specifications

With the MICRO and MACRO layer grids defined, the infrastructural specifications of the high-speed rail links can be obtained. The MACRO layer indicates where connections can be created, whereas the MICRO layer grid provides the set of nodes and edges to calculate the geographical and physical parameters of the new lines. By running the Dijkstra weighted shortest path (Dijkstra, 1959), it is thus possible to obtain HSR infrastructure specifications between an origin and destination. The model is therefore able to make a trade-off between cost and distance, between surface and underground nodes, thus building tunnels and lines across the case study area.

The results of the weighted shortest path calculations are two. Firstly, the length of the line is obtained, by multiplying the number of hexagons within the path by the average distance of 6 km (Section 4.5.1). Secondly the cost of the line is calculated as the summation of the weights of the edges traverse by the path.

Having the distance makes it possible to obtain the final travel time specifications by dividing the former by an average speed parameter. As previously introduced, the average speed of 220 km/h obtained by Donners (2016) with a regression analysis on a set of 30 existing and 30 modelled high-speed rail lines is used. This speed accounts for cruising speed, acceleration, and deceleration phases. Additionally, the regression also provides the detour factor for this mode, accounted to be 1.09. As explained in Section 3.3.1, this allows obtaining the final travel time. This completes the creation of the candidate investment pool, by defining the OD pair, the travel time, the construction cost and the distance. The complete list can be found in Appendix D.

Based on the model's validation in Appendix I, the model on average underestimate costs by 13% and overestimates distance by 12%. These differences can be attributed to many factors, such as the hexagon's level of detail, land-use patterns or different line designs. In some countries like Italy, HSR lines join the conventional network way ahead of the urban area, in Spain tunnels allow high-speed trains to penetrate the city from underground (Barcelona, Madrid), and in France is common to have high-speed rail station also outside the city (Paris, Lyon, Avignon). In terms of costs, the model is less accurate and leads to an underestimation of costs as compared to real cases. This can be attributed to external factors, as discussed in Section 3.3.1 IV, but also to the modelling itself. In the case of the Rotterdam – Amsterdam line for example, the 'Green Heart' had to be crossed with a more expensive tunnel instead of surface infrastructure, due to intense public opposition (Jacobs, 2006). Although this has been a more than justified decision, the model cannot grasp these details and therefore assumes a straight surface line. In case of mountain lines such as the Turin to Lyon connection, the big tunnelling projects are not accurately modelled due to the low performance of the detail level 6 of the hexagons, which can not replicate the terrain conformations in such detail.

Nevertheless, with 87% accuracy for costs and 112% accuracy for distance the model can be a starting point towards the modelling of high-speed rail lines considering terrain variations. In anticipation of the recommendations, by using higher resolution levels for the hexagons and mapping the land use better (e.g., natural areas), more accurate results can be obtained.

4.6 Base Network Module Specifications

This Section present the case study specifications related to the travel times in Section 4.6.1, the weighted travel utility in Section 4.6.2, and the 4-step transport model in Section 4.6.3.

4.6.1 Travel Times

For air the travel time is calculated by dividing the Greater Circle Distance by an average speed of 700 km/h as obtained with the regression analysis performed by Donners (2016). Car travel times are obtained by using the OpenRouteService between the cities' coordinates, adjusted with a detour factor of 1.2 (Donners, 2016). In the work by Grolle (2020) it has been shown that the results of this API are accurate, and comparable to values obtained with Google Maps or Rome to Rio.

Finally, rail travel times are calculated. Given that rail's OD travel times are a result of the weighted shortest path across the MACRO layer grid, the edges of the latter need to be initialized. As explained in Section it is assumed that rail is comparable to car in terms of travelled distance, and thus using the parameters obtained with OpenRouteService, a detour factor of 1.15 and an average speed of 110 km/h (Donners, 2016), it is possible to finally calculate the travel time and initialize the respective edge. In regard to HSR, travel times have been already obtained with the weighted shortest path and speed of 220 km/h as explained in Section 4.5.3. Table 13 summarizes the travel time calculation parameters and methods.

Table 13 - Travel time calculation parameters

	Speed (km/h)	Distance (km)	Detour Factors
CAR	100	ORS	1.2
PLANE	700	GCD	1
RAIL CONV.	110	ORS	1.15
HSR	220	Own Calculations	1.09

4.6.2 Travel time & Weighted Utility

The weighted time utility is obtained by weighing additional time components to the travel time for each mode. The final obtained utility accurately evaluates the perception that travellers have of travel time when undertaking a trip.

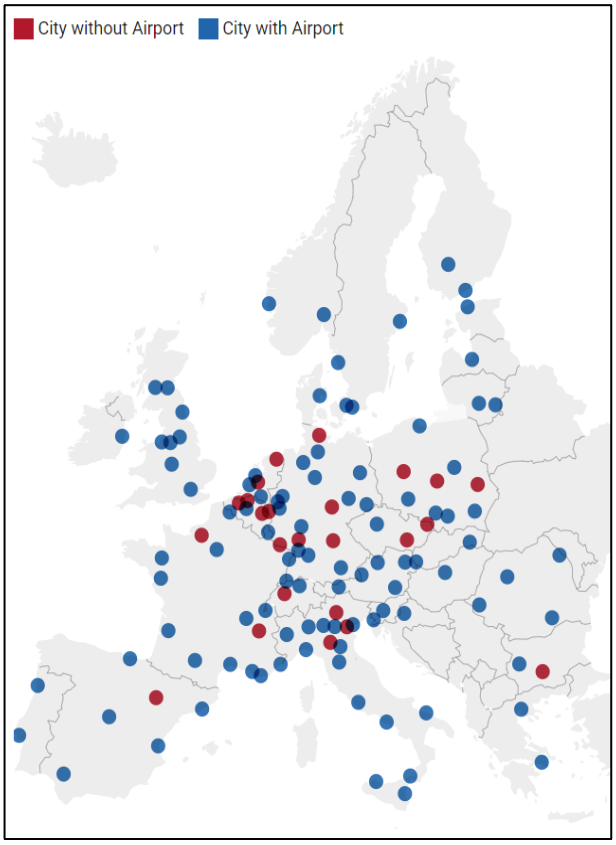


Figure 28 - Cities with airports (blue) and cities without airport (red)

Air travel waiting time is measured as the procedures of check-in and security checks before boarding and is assumed to be 110 minutes based on Park et al. (2010). For the exiting waiting time, an arbitrary 30 minute parameter is added to consider baggage collections, potential customs check and exiting from the arrival hall. For access and egress times, the values are obtained differently. For the cities that generate relevant levels of air traffic, an airport is paired as if existing. For this purpose, IATA data has been retrieved through API and the passengers flows from Eurostat (2023). For cities without an airport, they are paired with the closest possible facility. Access and egress times are thus obtained with OpenRouteService's API and a detour factor of 1,61 (Donners, 2016). Figure 28 displays cities with an airport in blue and the cities without one in red.

The only additional time parameter for car is a 10% penalty of the total travel times to simulate pauses along the trip. For rail, waiting time is assumed before the trip to look for the platform and reach the carriage. Therefore 15 minutes are added to the utility.

Access and egress parameters for rail are obtained based on the size of the urban area, measured by its radius. By assuming that the station is at the centre of the circle and that the average location distance is ¼ of the radius, the final access and egress times are obtained by dividing the latter value by 30 km/h and adjusting it with a city detour factor of 1.1 (Donners, 2016). The surface values are instead obtained for each Functional Urban Area from the OECD database (OECD, 2019). This allows having city specific values that vary based on the average distances between city locations and the centrally assumed main train station. Finally, Table 14 summarizes the parameters for calculating the weighted time utility for all modes.

Table 14 - Weighted time utility calculation parameters

	Access	Waiting (h)	Exit Waiting (h)	Egress
Weight	1.36	1.5	1.5	1.36
CAR	-	10% pause	-	-
PLANE	ORS	2	0.5	ORS
RAIL CONV.	Own calculations	0.25	-	Own calculations
HSR	Own Calculations	0.25	-	Own calculations

The demand is geographically mapped, and the necessary data initialized. The following steps assess the demand potential and the behaviour of the latter when travelling between the cities, by presenting the 4-step transport model specifications.

I Trip Generation

This stage quantifies the number of trips that each urban area generates annually. The formulation is taken from Donners (2016), who assumes that the trip production potential equals the trip attraction one. Each city generates trips annually based on the population volumes and the GDP per capita, meaning that bigger and richer cities account for more movement of people. Furthermore, Donners (2016) cites the works of Goeverden et al. (2010), which estimate that an average European undertakes 8 to 9 trips every year.

The production and attraction potential can therefore be calculated by multiplying the ratio of the GDP per capita against the average of the case study, by the product between the population and 9 yearly trips. Figure 29 shows the trip generation potential of each city in relation to its population. In total, for the 125 cities considered in the case study, 1.96 billion trips are generated.

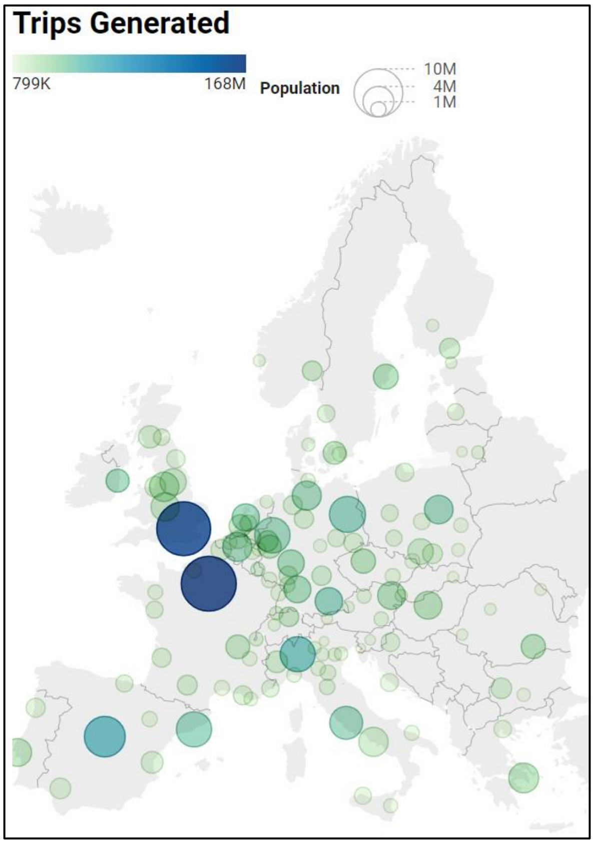


Figure 29 - Trips generated by each urban hub of the case study in relation to its population

II Trip Distribution

Following the doubly constrained gravity model of Section 3.3.3, the previously obtained trips are then distributed among the countries based on the degree of attraction between nodes and on the attraction and production constraints. The models components, as calibrated by Donners (2016), are here explained numerically in Table 15. The author finetuned these parameters based on a subset of cities for which travel data is available. Three barriers are identified as: Country borders, language barriers and Schengen borders. Based on the presence of barriers between an origin and a destination, their values reach a maximum 12,55, which is multiplied by the great circle distance $D_{i,j}^{k}$. k is the sensitivity to distance and l is a gravity constant. Trips within a city are not generated.

Table 15 - Numerical values for the parameters of the trip distribution (Donners, 2016)

Parameter	Variable	Calibrated	R^2
k	1,4		
l	-	0,00001366	91%
Country barrier	-	4,03	98%
Language barrier	-	6,50	83%
Schengen barrier	-	2,02	90%
Total	-	12,55	90%

The doubly constrained gravity model version of Donners' original formulation behaves differently when compared to previous results, with trips distributed more evenly thanks to the application of production and attraction constrains. Figures 30 and 31 provide insight for two city cases: Helsinki and Amsterdam.

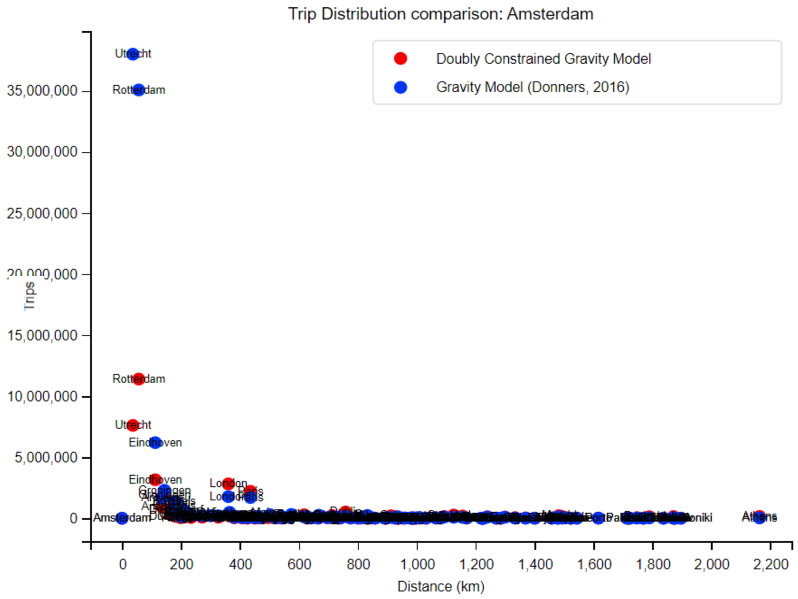


Figure 30 - Trip distribution comparison for Amsterdam

This means that OD pairs that previously had remarkably high traffic flows score lower values, whereas connections with very low trips now account for more trips. This benefits especially eastern and northern European cities, as well as more peripheral urban hubs likes Lisbon and Athens. At the same time, there are some specific geographical regions that are underperforming compared to the original gravity model, such as major urban centres in Germany, the Netherlands, UK and Belgium. Nevertheless, this does not have a significant impact on the trip distribution, as previous values for these countries were high, while now are more in line with the rest of the case study countries.

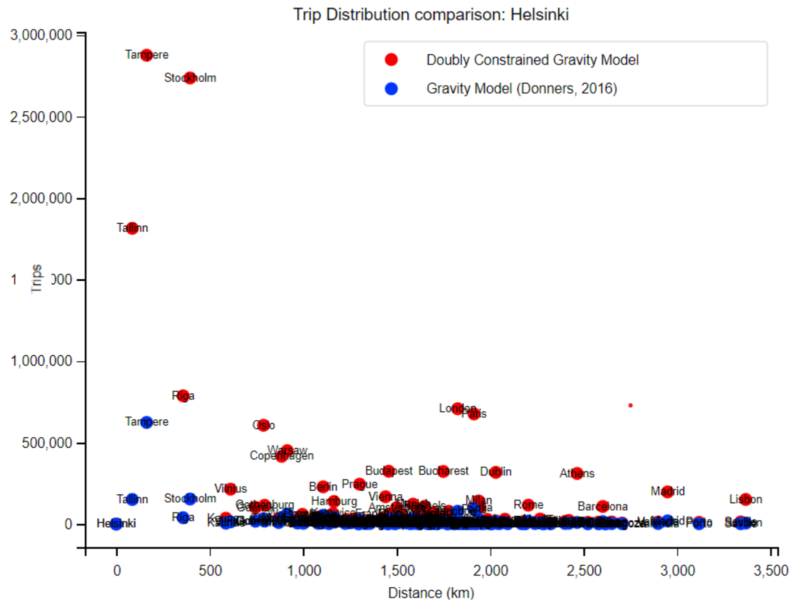


Figure 31 - Trip distribution comparison for Helsinki

The newly formulated doubly constrained trip distribution function has thus reduced the divergence between countries and balanced out the distribution of trips across the destination choices for each single city.

III Mode choice

The mode choice is based on the principle of regret minimisation as formulated by Chorus et al. (2008). For the travel time sensitivity parameters, β is chosen to be -0.01 and μ equals 1. The final regret value is than calculated as the Logsum of difference in weighted travel utility between mode, and used to obtain choice probability that travellers attach to each mode.

IV Trip assignment

The demand for each mode is assigned to the network to analyse travel patterns. Rail, unlike car and plane, uses an All-or-Nothing approach with no capacity constraints, assigning passenger volumes to the shortest path between origin and destination.

The end of the base network construction completes the data collection part of the first two Section of the model. The built data sets are now inputted in the last iterative network growth Section, which will iteratively evaluate and invest in high-speed rail links and model the HSR network growth strategies.

4.7 Iterative Growth Module Specifications

The last block performing the iterative HSR investments and modelling the network expansion is here presented. Section 4.7.1 addresses the corridor construction, Section 4.7.2 the corridor evaluation, Section 4.7.3 the economical scoring of the corridors, Section 4.7.4 the investment process and lastly Section 4.7.5 addresses the network update phase.

4.7.1 Corridor Construction

Once the links have been defined with the MACRO layer grid (Section 4.3.1), they are expanded into corridors to better map the infrastructural design of potential HSR lines. The size of the corridor pool is determined by k, while the feasibility in terms of maximum additional travel time allowed over the original link is defined with TT_k. As obtained in Section 4.4, k is chosen to be 20, which is the calibrated value that allows to include all existing high-speed rail corridor alternatives existing up to 2019. TT_k is defined as 30% more travel time over the original link. Finally, from the original 450 links, the candidate investments pool is extended to 2260 options.

4.7.2 HSR Candidate Investment Evaluation

Once the candidate investments have been obtained, the iterative network expansion can start. The first step is to evaluate the corridors one by one, by initializing the new and improved HSR travel times within the MACRO layer grid and computing the shortest path for all the OD pairs. This returns the travel time savings for each OD, as well as the new weighted travel utility which allows to compute the new mode choice and thus number of passengers shifting towards HSR.

The monetary travel time savings are obtained by assigning a specific value of time to each of the travel time components in a trip (i.e., access, egress, waiting and in-vehicle time). Furthermore, these values vary per country as different purchasing powers affect the willingness to pay for travel times savings. Section 3.5.3 explains the methodology to obtain different weighted values of time per country. The latter are based on the Dutch value of time from the work of Kouwenhoven (2014), adjusted by Grolle (2020) to 50 €/h for in-vehicle time, 75 €/h for waiting and 67.5 €/h for access and egress times. These values are subsequently corrected for inflation and adjusted to 2019 prices, resulting in 58 €/h for in-vehicle time, 87 €/h for waiting and 79 €/h for the Netherlands. Subsequently, these are adjusted for the other countries, obtaining the values presented in Table 16. The full list of country specific VOTs is reported in Appendix F.

Table 16 - Monetary Values of Time (VOT) for the different trip stages (€/h) (2019 prices)

Country	PLI Index	VOT In-Vehicle	VOT Access/Egress	VOT Waiting
Netherlands	1.17	58	79	87

The externalities that are included in the final benefit estimation are accidents, air pollution, climate change, noise, congestion, habitat damage and well-to-tank costs. For each mode, the summation of the externalities is reported in Table 17. These values have been obtained from a report commissioned by the European Union (CE Delft, 2019), and represent the €-cent costs that can be associated to each passenger every kilometre travelled by a specific mode. Car incurs in the most cost, mainly due to the high number of incidents and to the congestion factors. Air travel scores high in air pollution and noise externalities, as well as well-to-tank given the high fuel usage. Rail travel is the less impactful mode of transport, having some impacts in terms of habit damage and noise related to the infrastructure.

Table 17 - Total Transport Externalities for the different modes

	Air Plane	Rail	Car
Total	4.28	1.3	12.1

The value of time (VOT) and the identified externalities allows monetizing the benefits. In the following Section it is explained how the use of monetary values can improve the assessment of the transport potential of the single corridors.

4.7.3 Financial Feasibility

With the benefits defined for each corridor, this is financially evaluated by determining whether the benefits outweigh the construction and maintenance costs. The methodology for this financial assessment can be found in Section 3.5.3. The final NPV and BCR measures are obtained by discounting the yearly cashflow, calculated as the difference between benefits and costs, over a certain time period. For this purpose, the guidelines of the European Commission are adopted (European Commission, 2014).

To properly cover the project cashflow forecasts, an appropriate time horizon must be chosen. The definition of such parameter has a huge impact on the appraisal process as it can significantly influence the magnitude of benefits and costs. For the EC the average operational lifetime for all types of railways is 30 years but can be extended in case of unusually long construction times (European Commission, 2014). How long a high-speed rail line can last is still rather unclear, as very few lines have reached age and have been built with more innovative techniques. More recent studies on HSR specifically, have provided different lifetime values. Kortazar et al. (2021) undertook a lifecycle assessment of the Spanish high-speed rail network, considering 60 years of lifetime. De Bortoli et al. (2021) considered different lifetime parameters for its life-cycle assessment of a French HSR line: 30 years for the rails, 100 years for the engineering structures, 15 years for gravel bed and 30 years for concrete and steel elements. With the focus of this thesis being specifically on infrastructure, higher lifetime parameters might be more in line. Considering all studies and guidelines, the final project horizon is thus considered to be 50 years. This also aligns with the oldest European HSR lines (e.g., Rome-Florence, Paris-Lyon), which in the last

50 years have received period maintenance but not major reconstruction works. The operational lifetime does not include the 15 years of average construction time (European Court of Auditors, 2018).

Furthermore, the building costs of HSR infrastructures are usually composed of three main cost categories according to UIC (2005): The planning and land costs (5%-10% of total investment), the infrastructural building costs (50%-70%) and compensatory works (Barron, 2009). Therefore, a 10% planning costs are considered in the first 8 years of construction, while the remaining 90% will be spent during the remaining 7 years. Lastly, periodic maintenance costs are included in the costs cashflow once the infrastructure has been completed. These are considered to be around 0.03% of the total investment cost, obtained according to values of UIC (2015).

The discount rate used to discount future capital values to current prices, is taken from the EC guidelines of 2014 (European Commission, 2014). The value used is therefore 4%. Finally, the NPV and BCR calculations are performed for all the candidate links considered, ranking mutually exclusive options based on NPV and investment alternatives based on BCR. The resulting set is further ranked based on BCR, and the best scoring investment considered for construction.

4.7.4 Investment decision

The best scoring candidate investment is therefore the HSR connection generating the most utility for the passenger demand compared to the costs incurred for its construction. This option is considered and chosen as the investment decision. These are carried out if the budget available at that time step covers the infrastructural costs (Section 3.5.4). The latter is the summation of the yearly contribution by countries as a share of their GDP. Table 18 provides an overview of the historical yearly spending for the four European countries with HSR as a share of their GDP. The final average yearly spending is then applied to all other countries, as shown in detail in Appendix G.

Table 18 - Yearly spending in HSR as a share of GDP for the selected historical countries with HSR networks (European Court of Auditors, 2018)

Country	Total Investment (bn)	Operations start	Timeline	Yearly Investment (bn)	GDP (bn, 2019)	% of GDP
Italy	41.9	1992	31	1.4	1796.6	0.08%
Germany	34.1	1991	32	1.1	3473.3	0.03%
France	40.4	1981	42	1.0	2437.6	0.04%
Spain	54.1	1992	31	1.7	1245.5	0.14%
	% of GDP spent yearly in HSR for the 4 European countries with historical HSR networks					0.07%

Finally, for all countries involved, the total yearly budget is roughly 12.5 billion euros for HSR infrastructural investments. If the corridor cost is within the budget constraint, it can be built. If the corridor is not within the budget constraints, it means that the model saves the current budget and iterates to the next year, where it receives an additional yearly investment capital round. This process assumes that the budget is saved until the best scoring link can be build.

This marks the end of the case study Section. The following chapter presents the results of the model applied to the case study, discussing the main findings and highlighting the model functioning dynamics.

05

Results

Italo EVO, NTV, first private high-speed rail operator in Europe
Italy

5 Results and Discussion

In the following Sections, the methodology described in Chapter 3 is applied to the case study presented in Chapter 4. Firstly, the modelling scenario and the obtained results are analysed in Section 5.1, while Section 5.2 provides the discussion of results and Section 5.3 discusses the model's assumptions and limitations. All the additional material, including the base network, the iterative investment evolution and the obtained scenario specifications, are collected and presented in Appendix H.

5.1 Results

The iterative network growth module applied to the case study is based on an initial network configuration shown Figure 32. The base network is composed by all existing dedicated HSR infrastructures in operation by 2023, by dedicated HSR lines under construction and by all dedicated HSR projects that have received funding. From this selection, all dedicated HSR sections that cover less than half of the distance between the cites they are linking are not included, so to understand if the model considers them feasible investments and thus suggests the completion over the entire length (e.g., Nuremberg-Munich, Stuttgart-Munich, Zurich-Milan).

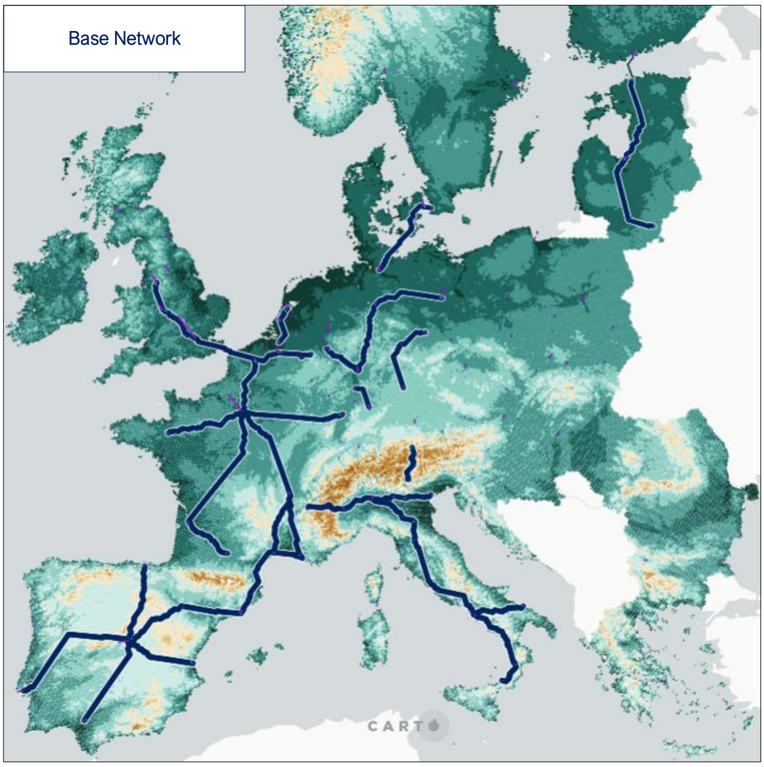


Figure 32 - Modelling scenario base network

Additionally, an exception for mixed traffic lines up to 250 km/h is made only for infrastructures currently under construction, such as the Brenner tunnel, the Fehmarn tunnel, and the Rail Baltica project. Although these connections are not properly high-speed, it is highly unlikely that a parallel dedicated HSR line could be considered as a candidate investment in the future. To initialize the scenario, the $Built_{LINK}$ matrix of Section 3.5.3 is loaded with the HSR travel times for the links considered to be operational. Subsequently, travel time, mode share and utility matrices are initialized accordingly. Figure 33 presents the graphical evolution of the network. The complete iterative set of investments and the graphical visualizations using CARTO can be found in Appendix H.

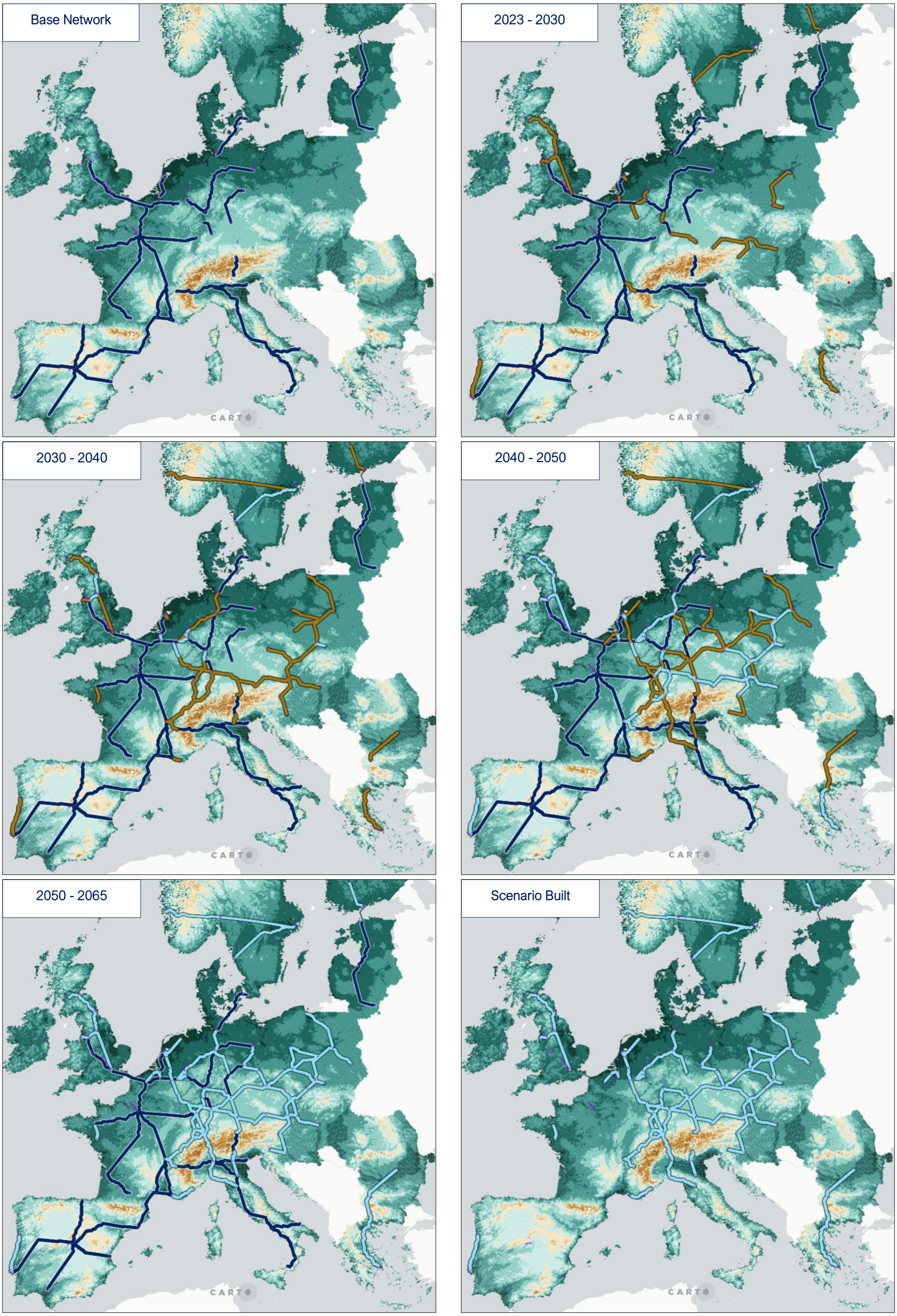


Figure 33 - Network evolution timeline. Existing lines in red, lines under construction in green, and completed lines in orange

By analysing the economical implications of such network expansion, Figure 34 highlights the iterative evolution of the model based on three indicators: The Net Present Value (NPV), the investments, and the Benefit-Cost ratio (BCR). The timeline considered refers to the investment period from 2023 to 2050, with the candidate link choice based on the highest BCR, represented by the yellow markers. Dark blue bars indicate the NPVs of the candidate options the year in which they are chosen, given the allocated investments represented with the light blue bars.

From a first overview, it is possible to understand how the iterative pattern is strictly guided by the dynamic interaction between the measured benefits of the new investments and the infrastructural costs, which represent the physical characteristics of the line. The initial investments, such as the Brussels to Antwerpen and Dusseldorf to the Ruhr Sections, show how the existing network influences the evolution displaying preferential attachment features (Barabasi et al., 1999). At the same time the opposite is shown by subsequent investments such as Stockholm to Gothenburg and Katowice to Kracow Sections, where significant travel time improvements or demand volumes influence more the investment sequence rather than the existing network. Furthermore, path dependency dynamics are evident, especially when the BCR is peaking, relating investments' utility to previous iterations. To further analyse Figure 34, the red circles are used, which highlight some functioning mechanism in more detail.

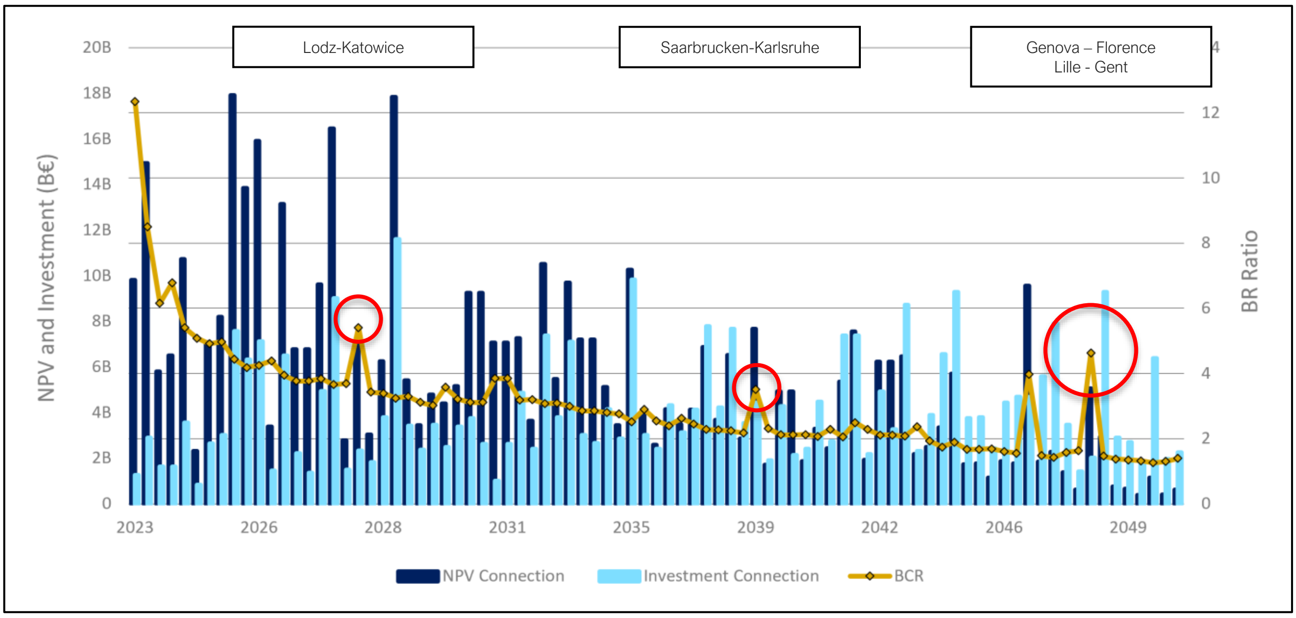


Figure 34 - Iterative evolution of NPV, BCR and investment costs

The first circle on the left identifies the 2028 investment between Lodz and Katowice in Poland. This choice follows closely the one before of connecting Lodz to Warsaw, showing how the model expands the network from a central high-value hub (Warsaw) towards other centres of interest (Lodz and Katowice). Here, path dependency can be recognised since the Lodz-Katowice connection was not that profitable until the Warsaw-Lodz has been built. This expansion mechanism from important urban hubs or existing Sections outwards is recognizable especially at the beginning of the iterations, highlighting the 'richer get richer' network expansion dynamic.

The second circle highlights the 2039 Saarbrucken-Karlsruhe investment. This choice is the consecutive iteration of the Luxembourg-Saarbrucken investment. In this second case, the model choses the missing link between the Brussels area and south-west Germany, establishing a connection between two densely populated regions and two previously unconnected network Sections. Path dependency is recognizable also in this case, as the BCR of the investment is strictly related to the previous iteration. This second modelling mechanism of connecting regions and networks over longer distances is visible especially in the middle stage of the iterations, when the most important urban centres have already developed an initial network around their influence area and thus seek to extender their reach over longer distances.

The last two peaks highlighted are the Genova to Florence and the Gent to Antwerp investments. Both cases are a result of the model choosing to build alternative paths to existing infrastructure. Genova to Florence is part of the sequential investment Milan-Genova-Florence corridor, parallel to the existing Milan-Mediopadana-Bologna-Florence line. Gent to Antwerp is part of the sequential investment Lille-Gent-Antwerp, which is parallel to existing Lille-Brussels-Antwerp corridor. It is observable that this densification of the network happens especially in later stages of the iterative process when the model invests in those shortcuts where there are still enough marginal benefits to be gained. Note that the Leeds-London investment, which is considered a short cut, is built quite early in 2029. Nevertheless, it's the last investment in the UK, and when accounting for higher VOTs, it can be considered in line with the dynamic evolution rule just explained.

Figure 34 shows therefore the main iterative mechanism, based on the dynamic interaction between benefits generated by the investments and the terrain characteristics represented by infrastructural costs. Furthermore, the model starts to build HSR infrastructure from main urban centres and existing network sections, then over longer distances to connect networks, and finally densifies the infrastructure where there are still benefits to be gained from shortcuts.

To better define the benefits' composition and understand their behaviour, Figure 35 shows the iterative evolution in this regard. Two additional indicators are added: The total passengers shifting to HSR, and the travel time improvement over the new connection. The latter two values are normalized within the range 1-100 and are shown in the graph by the black line and the red line respectively. This allows to understand how the investments have mainly three specific functions within the iterative process, leading to different types of benefits generated, as explained in the following paragraphs.

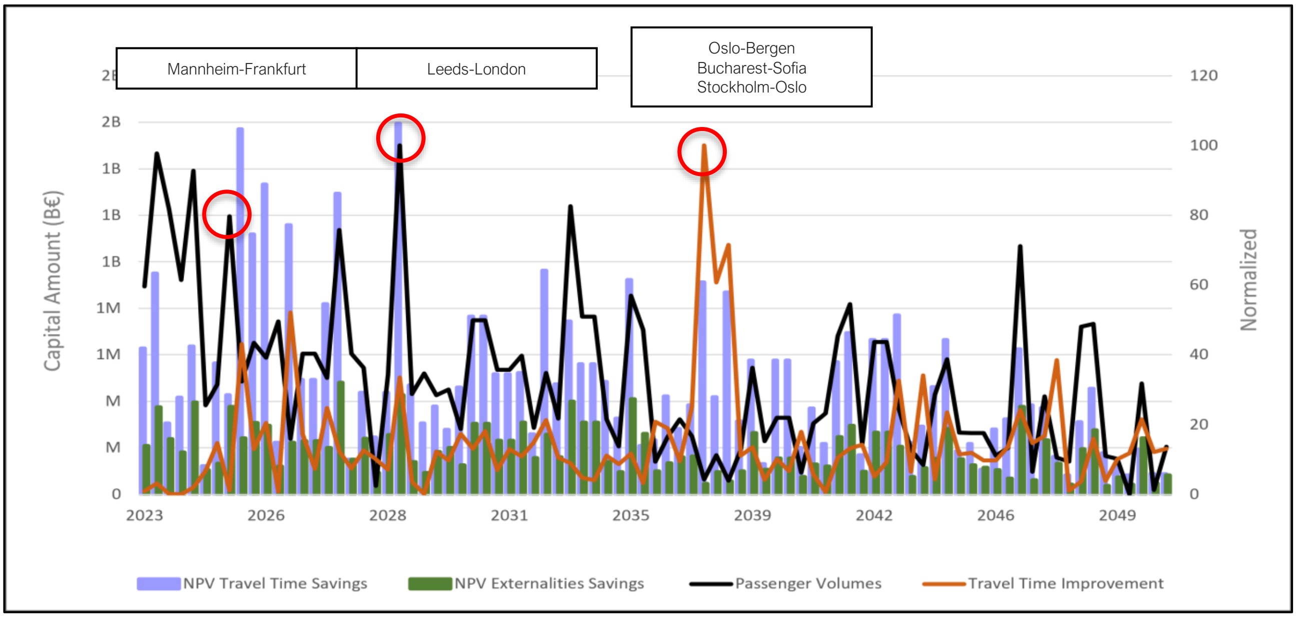


Figure 35 – Iterative evolution of travel time and externality savings

The first red circle, the Mannheim-Frankfurt connection, with low travel time improvements but high volumes of passengers shifting, denotes type one investment which links two previously unconnected networks. This eliminates the discontinuity gap and improves competitiveness of longer OD pairs for a large number of passengers already travelling by HSR. The same type of connection can be found for Brussels to Antwerpen (2038) and from Cologne to Aachen (2039). Note that the high volume of passenger is influenced by the assumption that all people traveling by conventional rail shift to HSR if the latter becomes operational for that section.

The second red circle, highlighting the Leeds to London connection with both consistent travel time improvements and shifting passenger volumes, denotes type two investment building a shortcut parallel to the existing infrastructure. In this case, once all major Sections have been built (London-Birmingham-Manchester-Leeds), the relatively consistent travel time saving potential of the shortcut can shift consistent volumes of traffic from the existing sections. The same can be witnessed with the investment for the Milan-Genova-Florence line (2046), Lille-Gent-Antwerp (2048), or Zurich-Strasbourg (2050) connection, all creating a shortcut that densifies the existing network coverage.

Finally, the last red circle identifies type three investment, which links distant centres and is located mostly in peripheral areas. The highlighted investments are the Oslo to Bergen, Bucharest to Sofia and Stockholm to Oslo lines. Given the larger distances, travel time improvements are significant. On the other hand, these urban centres are peripheral to the densely populated central areas of the case study, therefore the trip distribution yields low passenger volumes as compared to central ODs. Note that the VOT has a significant impact on the magnitude of these peaks. Similar cases can be found also at the beginning of the iterations, namely the Stockholm-Gothenburg (2024) and Thessaloniki to Athens (2026) connections.

In conclusion, the iterative display of benefits does not suggest a specific logical behaviour behind the choice of which type of investment to build. Nevertheless, this analysis allows to understand what drives the composition of benefits and how these are strictly related to the function that each investment has within the network structure. Furthermore, the definition of the iterative evolution mechanism can now be enhanced as the dynamic interaction between demand volumes, travel time improvements and infrastructural costs.

Shifting the focus more on analysing country specific parameters, Figure 36 shows the network evolution in each nation, based on existing and newly constructed HSR lines. From an initial base network length of 10951 km, the model invests in additional 13203 km of new lines, bringing the total network length to 24154 km according to the budget allocated (Section 4.7.8). Substantial investments are attracted by Germany and Poland, followed by Switzerland, Czeck Republic, and the United Kingdom. These nations dominate the expansion thanks to the relationship between population density and network centrality. Some countries on the other hand do not see any investment on their national territory, with Spain standing out as the country currently with the longest network without any evolution. This can be attributed to two main reasons. Firstly, the current network and existing plans could already exploit the HSR potential of the specific country, as for example along the Rail Baltica line or in Denmark. Secondly, the investments could also be limited by the selection of urban centres in the case study, where cities with connection potential might not have been included. This could be the case of Spain, where for example minor cities that are currently subject to future infrastructural expansions are not considered (IRJ, 2022).

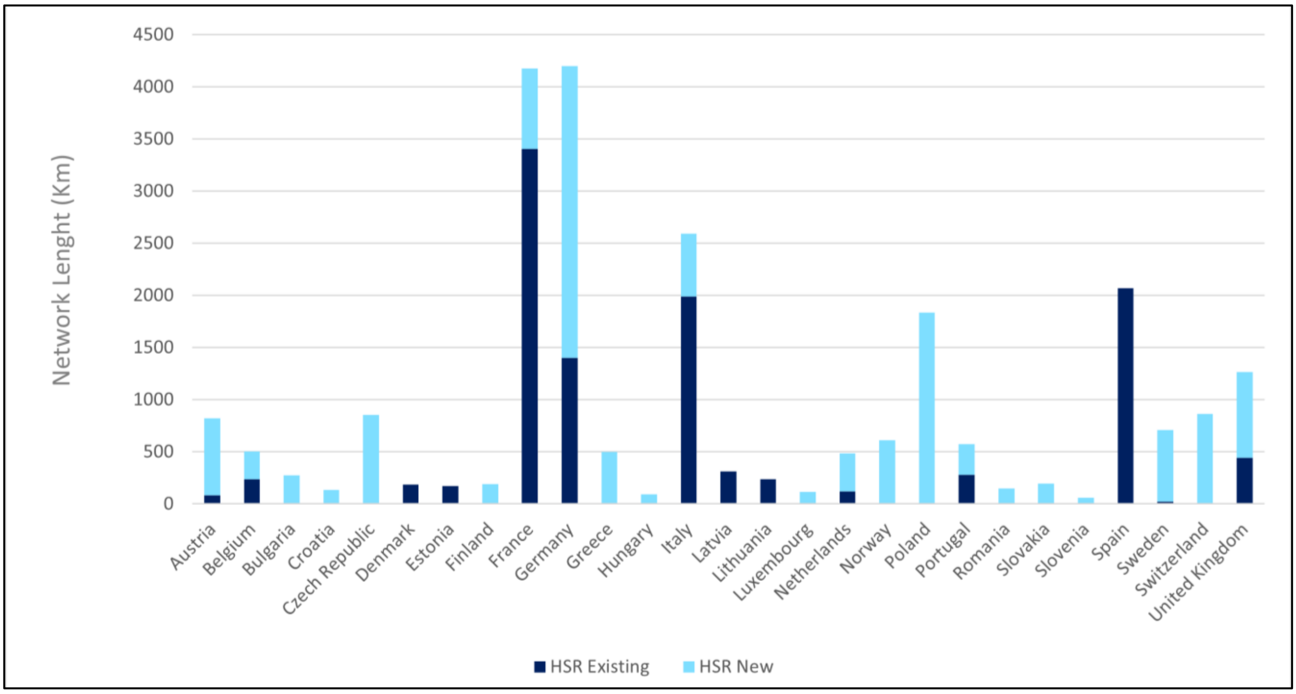


Figure 36 - New and Existing HSR infrastructure per country

Continuing with the country specific analyses, Figure 37 reports the present monetary travel time and externality savings per country. The present benefits per country reflect to a certain extend the infrastructural developments for each nation in Figure 36, but are significantly influenced by national VOTs, as explained in Section 3.5.3. The most interesting finding is that countries that in the previous figure do not have any network developments, witness some benefit generation in Figure 37. This demonstrates the existance of a spill-over effect from investments in neighbouring countries, where the improved HSR utility influences mode choice also across border.

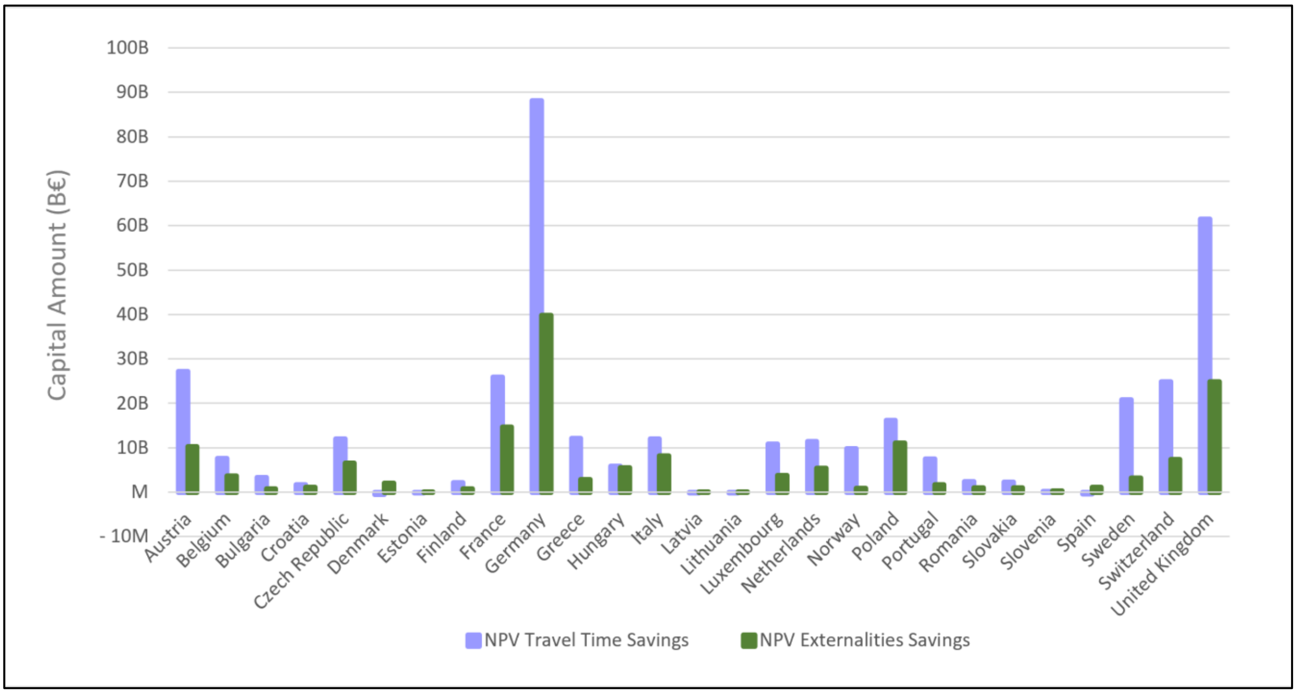


Figure 37 - Scenario Country specific net present travel time and externalities savings

Furthermore, in Figure 37 it also possible to observe the impact of combining the RRM choice model (Section 3.4.4) with the assumption that only travel time is considered when assessing mode choice (Section 3.2). The RRM computes new mode shares every time there is a change in utility, proportionally to the the utility differences between modes. This means that when rail travel time improves, the volume of passengers shifting to rail depends on how other modes perform compared to rail. In the case where rail becomes very competitive many passenger shift, whereas when rail's travel time is improved but still remains uncompetitive with air for example, the shift is significantly lower. Nevertheless, the small percentage of travellers of the latter case incurrs in a disutility, which is then translated into negatvie monetary travel time savings. For countries that generate good benefits, these negative values are easily masked. But for countries which do not have positive benefits, such as the one without network evolution in Figure 36, this negative travel time savings need to be acknoledge and considered during the model formulaiton process. For this work, given the relatively low impact of this effect, the disutility is kept. For future work it is reccomedned to restrict mode choice calculations within a certain distance range, prevent eccessive negative results.

For the final analysis on national evolution dynamics, Figure 38 presents the gains that each country has from the investment scenario, based on how much investments they have received and on how much they have contributed to the investment budget. Monetary investments in new HSR infrastructure are presented in light blue, the contribution to the budget is marked in dark blue and the BCR for each country is given by the yellow marker. Finally, countries are ranked based on the latter indicator. For countries that do not benefit from the investment plan, their BCR falls within the grey area. Note that the magnitude of both the investments received and the budget allocations are related to each country's infrastructure cost structures and GDP respectively (Sections 4.5.1 and 4.7.4)

The first category of countries with a positive return on investment can be found on the left from Luxembourg to France. The second category, with a negative BCR goes from Romania to Latvia. In the latter category, countries that have received infrastructural investments but have a negative BCR are Romania, Finland, Italy, and Slovenia. Figure 38 also shows that the return on investment (BCR) is not always linked to receiving more than contributing, such as for Hungary, Sweden the United Kingdom, and the Netherlands. This highlights how these countries witness rather small network expansions, but of high value, receiving investments for potentially key infrastructural connections. Nevertheless, all countries with a negative return on investment have contributed more than what they have received. This suggests that compensation measures could be needed for receiving the approval of all countries to such an investment plan.

Major contributors, such as France, Italy, and Spain receive less than what they give, due to their networks being already quite developed. For the United Kingdom, the contribution is higher than the received investments although its HSR network witnesses' consistent development. Here the geographical conformation of the country allows for quite a short linear network expansion, which does not require as much funding as for Germany for example. For the latter, given a central vast and distributed network structure, major funding is required to cover the infrastructural development. Finally, Luxembourg has an incredibly high BCR, given that the contribution to the budget is significantly lower than the benefits of having fast connections to the Benelux area and southern Germany.

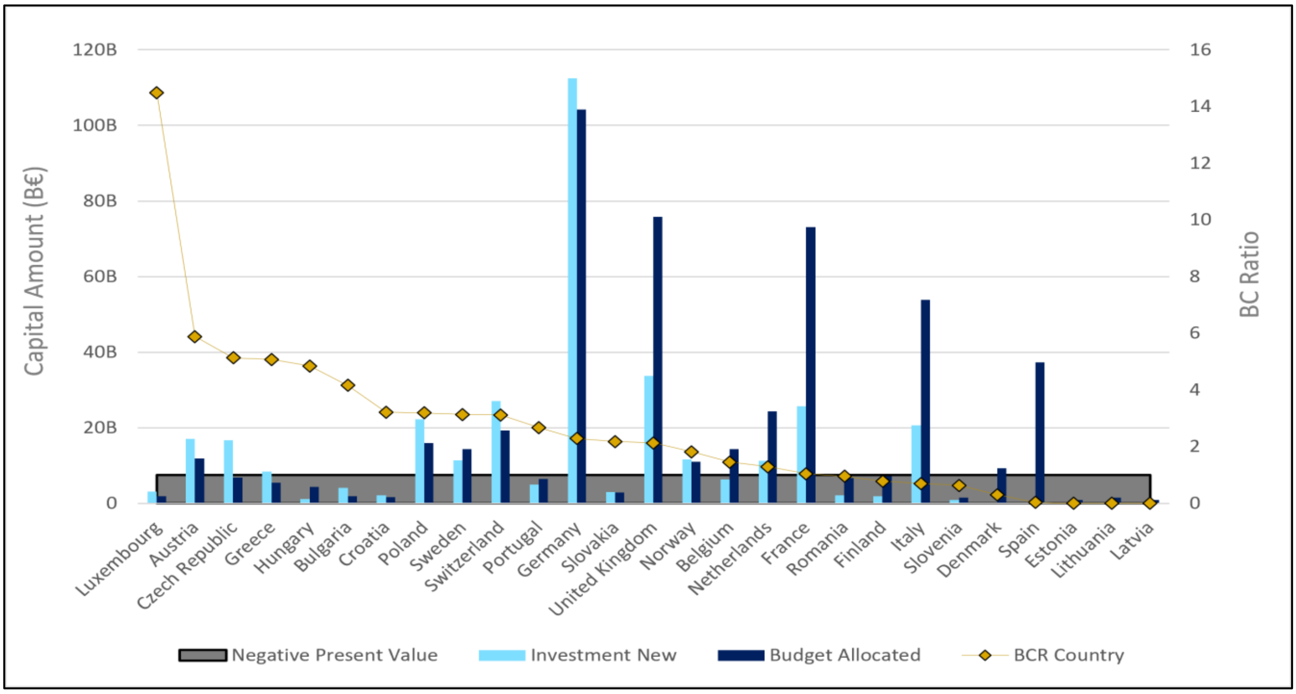


Figure 38 - Scenario Country specific budget contribution, investments received and BCR compared to EU BCR

Regarding the modal split achieved within the investment scenario, Figure 39 highlights the iterative evolution between 2038 and 2065, when the invested infrastructure becomes operational. The grey line indicates rail's mode share change in relation to the previous iteration. In Figure 39, the mode share evolution can be considered relatively linear. Rail shifts from 13% at the beginning of 2038 to 27% at the end of the time scope, mainly affecting air mode share. The red circles show where rail's mode share improves most from the previous iteration. Interestingly, the majority of the peaks correspond to cross border connections where national networks are being connected, demonstrating the crucial importance for such investments.

The second red circle highlights the construction of several cross-border connections between Poland, Austria Czech Republic, and Germany, further highlighting how path dependency iteratively improves passengers' flows influencing economic feasibility of investments. The third and fourth circle show the connections between Italy and its neighbours, respectively Austria (Munich-Innsbruck and Trento-Verona) and Switzerland (Milan-Zurich). Finally, the fourth circle marks another international connection influenced by path dependency between Germany (Nuremberg), Czech Republic (Prague) and Poland (Wroclaw).

By further observing change rates, these are not induced by connections between big population centres. Instead, the significant increase in rail's mode share can be attributed to the connection of two previously separated national or regional networks, where big volumes of passengers already travelling with HSR see their utility extended by being able to travel over other networks as well. Therefore, Figure 39 shows how cross-border connections allow the model to eliminate discontinuity among networks and therefore significantly increase the utility or rail transport to further justify subsequent investments.

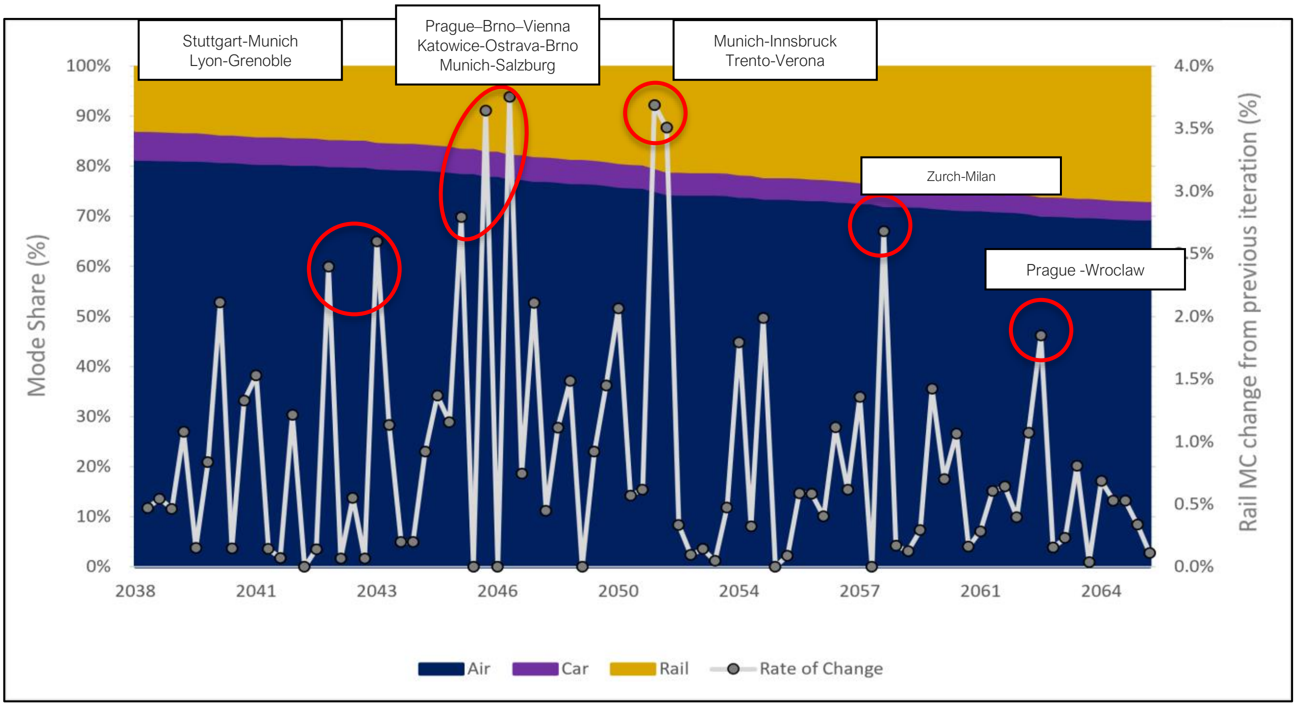


Figure 39 - Country specific iterative mode share evolution

Finally, Figure 40 shows the mode share in relation to distance. Within the modelling framework, rail and air are equally competitive at around 300 km in 2023, whereas this has shifted to around 600 km in 2065. This also means that most trips below 600 km, or almost three hours, are going to be by rail in 2065.

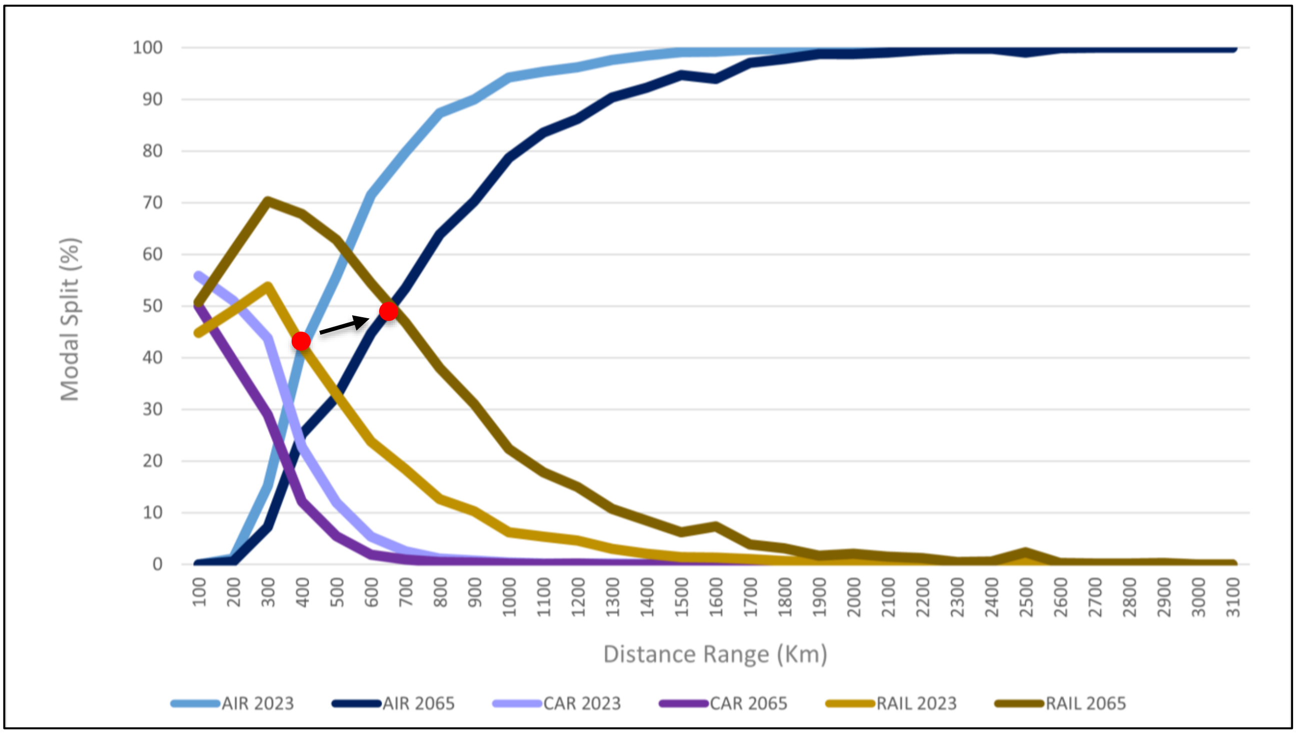
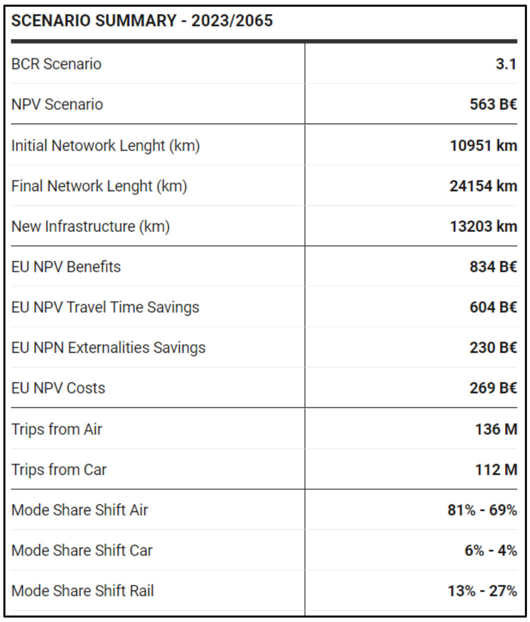


Figure 40 - Mode share shifts in relation to distance ranges

The shift in competitiveness could trigger several considerations. Firstly, it could be interesting for the rail industry when designing high-speed rail services. The same applies also for airlines now that some countries are considering banning short-haul flights. Secondly, the competitiveness could aid design policies to understand how to integrate different modes and at what distance to integrate them in order to achieve a balanced and better performing transport network. Finally, Figure 41 provides a general summary of the investment sequence presented in the previous paragraphs.



SCENARIO SUMMARY - 2023/2065	
BCR Scenario	**3.1**
NPV Scenario	**563 B€**
Initial Netowork Lenght (km)	**10951 km**
Final Network Lenght (km)	**24154 km**
New Infrastructure (km)	**13203 km**
EU NPV Benefits	**834 B€**
EU NPV Travel Time Savings	**604 B€**
EU NPN Externalities Savings	**230 B€**
EU NPV Costs	**269 B€**
Trips from Air	**136 M**
Trips from Car	**112 M**
Mode Share Shift Air	**81% - 69%**
Mode Share Shift Car	**6% - 4%**
Mode Share Shift Rail	**13% - 27%**

Figure 41 – Result summary

5.2 Discussion of Results

In this Section the results obtained in the previous scenario analysis are further discussed and confronted with the main findings identified in the literature. Section 5.2.1 provides a first analysis and discussion of the results, whereas Section 5.2.2 highlights the general functioning of the model. The following sections analyse the result showing the emergence of strategic hubs (Section 5.2.3), the implications of having a common budget (Section 5.2.4) or the degree of influence of different initial network configurations (Section 5.2.5). Finally, Section 5.2.6 present the potentials of a centrally coordinated decision-making process.

5.2.1 General Results Overview

The results presented in Section 5.1 provides an overview of the modelling dynamics within the case study context. The HSR network expansion highlights interesting developments for central and eastern Europe, as well as for peripheral areas and the United Kingdom. The countries that witness the highest network expansions are Germany, Poland, Czech Republic, Switzerland, the United Kingdom, and Austria. The network coverage is further densified between Switzerland and southern Germany, in Belgium, Poland and northern Italy. Finally, the emergence of peripheral long-distance HSR connections is modelled, such as between Athens and Bucharest, Stockholm and Bergen, Stockholm and Gothenburg, and between Lisbon and Porto.

Compared to the literature analysed, the obtained network configuration can be considered in line with the current initial TEN-T expansion plans, given that the currently revised ones have increased the core network coverage to almost all major regional networks. The white circles in Figure 42 highlight the key differences, which interestingly can be found mainly on cross-border sections. Despite the model has demonstrated the importance of establishing connections between national networks, the comparison with TEN-T plans could highlight the limitations of the model when it comes to estimate induced demand flows and wider economic benefits, as well as considering only dedicated HSR passenger lines for example.

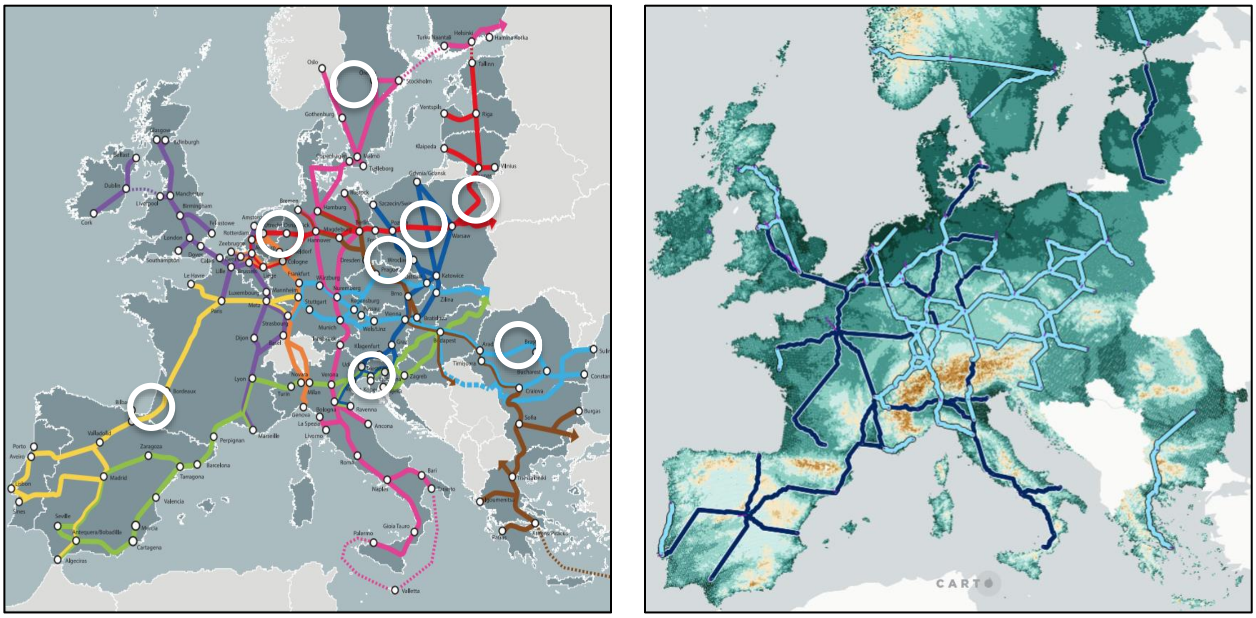


Figure 42 - TEN-T project compared to obtained Scenario network evolution

Furthermore, some differences can be also found when comparing the obtained network configuration with the line and frequency setting configuration modelled by Grolle (2020). In this case the author obtained some significant development along the Bordeaux-Bilbao, Amsterdam-Utrecht-Hamburg and Berlin-Warsaw Sections. Instead, this work had more development along northern Italy, Poland and between southern Germany and Switzerland. This comparison implies how service design, frequency settings and infrastructural capacity constrains could significantly impact the outcome of the sequential investment modelling. Note that these differences might as well be caused by considering different spatial structures, as for example with the exclusion of Nuremberg from Grolle's work, which in the scenario presented in Section 5.1 has a major hub role. Lastly, the different approaches used, optimization for Grolle and iterative growth for this work, might as well return different network design because of the different dynamics involved.

The total network expansion obtained for the scenario based on historical budget trends, accounts for roughly 13000 km of new lines, more than doubling the considered base network. When compared to reviewed works the results score lower, with Ernst & Young (2023) estimating roughly 35000 km of total network extension, and Deutsche Bahn et al. (2023) estimating 21000 km of new lines to be added by 2050. It must be noted that the latter two works assume a static network configuration to be completed for 2050. What the differences in results could suggest, is on one hand that historical budget trends, if shared among all countries, will not lead to the achievement of EU's goals. And on the other that the investments appraisal should be improved in terms of benefits estimation, so to potentially justify the profitability of further network expansions. Lastly, Deutsche Bahn (2023) does not account extra EU countries, such as the United Kingdom and Switzerland, which in this work demonstrate huge expansion potential, the latter especially as central hub for Europe. Nevertheless, some commonalities can also be found between the scenario and these studies, especially in terms of development potential, for which Germany and Poland score best in all three cases.

To achieve such expansion, the model forecasts a total of 269 billion euros of present investments, to be spend progressively between 2023-2050 for achieving a NPV of 563 billion euros. For Ernst & Young (2023) these values are slightly different and are based on three different costs per kilometre. Costs therefore range between 400 billion and 835 billion euros, and NPVs between 560 billion and 830 billion euros, with higher values linked to a bigger network expansion. Despite the network size differences between this work and the study, the BCR found by Ernst & Young (2023), ranging between 2 and 4, is comparable with the one found in Section 5.1. With costs estimations in this work which are significantly higher than the ones of Ernst & Young's (2023), and benefits estimated mainly on travel time, this suggest that the VOT values or the PLI indices return higher benefits than the one accounted by EY.

Finally, in the obtained scenario rail's mode share increases from 13% in 2023 to 27% in 2065. For this last comparison, values are less aligned with the two studies considered, which yield an increase in rail's ridership from 12% to 19% for Deutsche Bahn (2023), and from roughly 10% to 54% for Ernst & Young (2023). Here the marked differences can be attributed to the size of the networks considered and to how mode choice is modelled, by including other parameters such as price or by considering fixed mode shifts based on certain policy and demand shocks. For the final remark, both cited studies highlight how private vehicles dominate the mode share, whereas for the modelled scenario air travel is predominant. In conclusion, these differences in mode share suggest that the assumption of which parameters to include in mode choice, need to be carefully revised and expanded to accommodate more precise choice modelling considerations.

5.2.2 General Functioning of the Model

The main findings of Section 5.1 suggest that the model's iterative mechanism is characterised by the dynamic interaction between passenger demand, travel time improvements and infrastructural costs. The iterative process can be divided into three phases. It starts by building connections between the most important urban centres, continuing to expand over longer distances between networks, and concluding by densifying network areas that still yield improvement potentials. Nevertheless, preferential attachment is significantly constrained by the profitability of the edges, thus by the trade-off between spatial features (i.e., infrastructural costs and travel time savings) and node properties (i.e., passenger volumes). This can be seen in the initial phase, where the model invests in independent connections unrelated to the existing network due to high BCRs. The latter is not in line with the assumption included in the model by Cats et al. (2021), where new investments must be originated from the existing network. Lastly, the infrastructural investments carried out at each iteration can either yield high passenger flows, significant travel time savings, or improve both aspects at the same time. The model does not have a logical behaviour when investing in different types of lines, but this could be of valuable insight to understand the benefit composition of investment and consequently adapt the appraisal process. For example, the first type of infrastructure allows to shift high volumes of passengers without significant travel time improvements. In this case externality savings have a significant share of the benefits making it more a green investment rather than a functional one improving the connectivity or commuting times.

Figure 43 analyses the fist phase of the network evolution, between 2038 and 2043. The investments are allocated to highly populated areas with relatively short distances between urban centres and that are connected to existing networks, following the principles of 'the richer get richer' (preferential attachment). In the case study area, this potential is high for the Benelux region, the United Kingdom, the Ruhr area, and southern Germany.

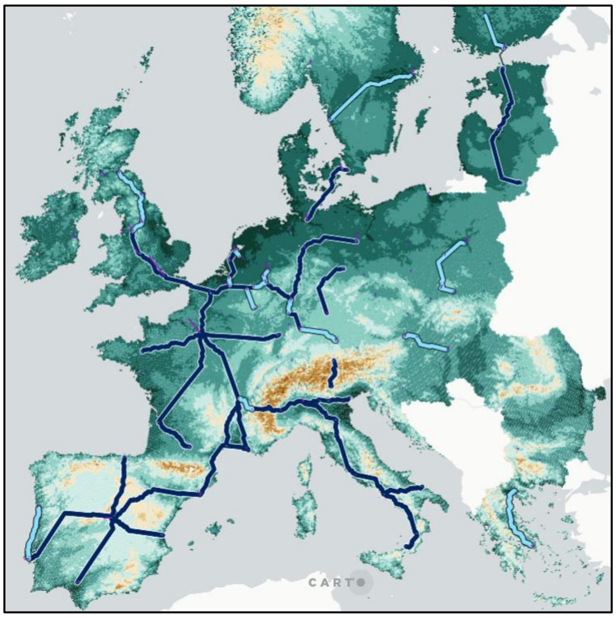


Figure 43 – 1st expansion phase, 2038-2043 evolution

On the other hand, the model invests in some connections that are not liked to the existing network, identifying new centres of importance along which new HSR lines can be built. This is the case of the Stockholm-Gothenburg, Warsaw-Lodz-Katowice, Budapest-Bratislava-Vienna, and Thessaloniki-Athens connections. In the second phase, lasting roughly 15 years between 2043 and 2058, the model builds those connections that still yield high benefits by increasing reach and connectivity, but that are less profitable due higher infrastructural costs over longer distances. In the second phase preferential attachment is less constrained by link profitability, as the best performing connections have been already built and the network is expanding progressively across the case study area.

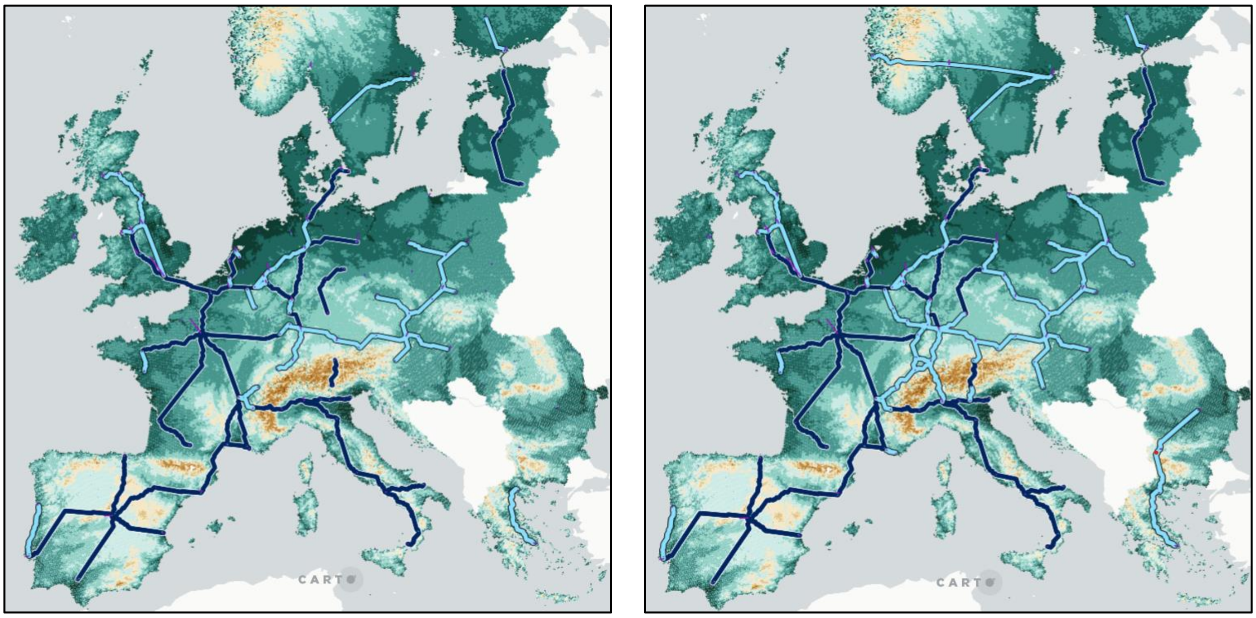


Figure 44 – 2nd expansion phase, 2043-2050 evolution (left) and 2050-2058 evolution (right)

Figure 44 depicts the expansion phase, where it is possible to recognise most of the previously highlighted rail's mode share spikes of Figure 39, which identify investments that improve connectivity between previously unconnected networks. This is the case of the cross-border connections through the alps or between Germany, Austria, Czeck Republic and Poland.

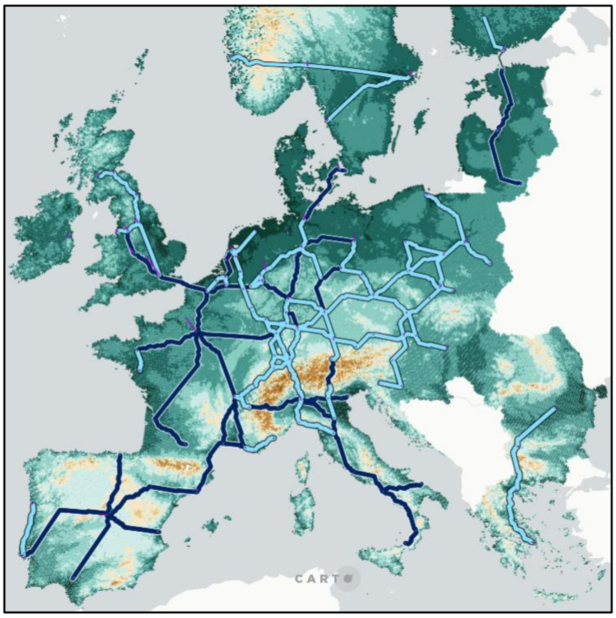


Figure 45 – 3rd expansion phase, 2058-2065 evolution

Finally, the last phase, from 2058 to 2065, shows the densification of the network along areas where still marginal improvements potential can be found. As can be seen in Figure 45, these are northern Italy, the Benelux region, Poland and along cross-border connections between southern Germany and Switzerland.

The value of time and distance also have a significant role, as the former influences travel time savings and the latter infrastructural costs. For example, higher values of travel time savings compensate for longer distances in Scandinavia, and lower cost compensate for lower densities in eastern Europe in phase one. This can also be attributed to the ability of HSR "to cope extremely well with a non-uniform reduction in density, with dense zones separated by deserted areas" (Ellwanger et al., 2001) thanks to lower travel times. Finally, preceding the discussion and potential policy implications, some countries without significant HSR infrastructure nowadays, such as the United Kingdom, Poland, and Czech Republic, shows great infrastructural potential. The evolution mechanism modelled in the results leads to similar conclusion when compared with the work of Pablo-Marti et al. (2017) and Cats et al. (2021), in terms of benefit evolution for the first and in terms of similar evolutionary patterns for the second.

5.2.3 The Emergence of Strategic Hubs

During the last phases of the model evolution, some geographical areas emerge over the others due to multiple HSR connections traversing them. This 'dense' locations can thus be considered as potentially hubs and are divided in two types.

The first type is represented by polygonal shaped centres formed by multiple close cities, where utility is high and investing in shortcuts is profitable. For scenario one, six cases are identified by the yellow hexagons in Figure 46: The Basel-Zurich-Bern, the Cologne-Ruhr-Aachen, the Stuttgart-Mannheim-Karlsruhe-Frankfurt, the Lille-Gent-Antwerp-Brussels, and the Brno-Bratislava-Vienna enclosures.

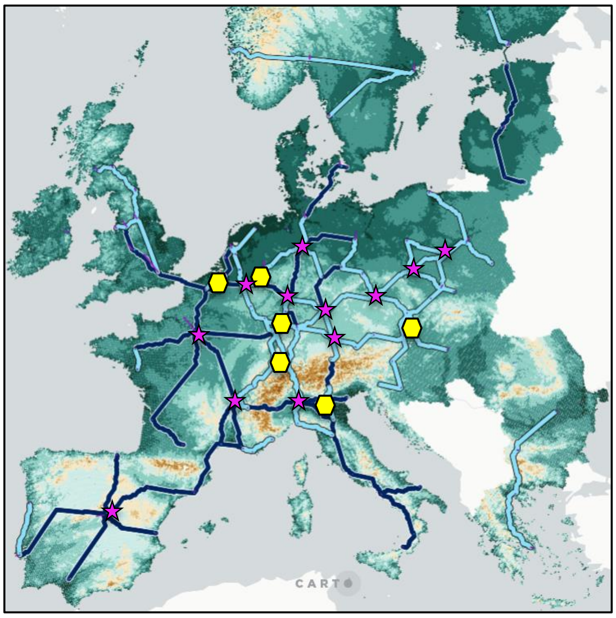


Figure 46 - Key HSR hubs identified as polygonal areas (yellow) or star shaped Intersections (pink)

The second type of hub has the form of a star shaped vertex, with 8 major cities with at least four branching connections, as highlighted by the pink stars in Figure 46. For these points there are no other cities within close distance for shortcuts, meaning that all the demand must pass trough these hubs. These cities are big urban centres such as Madrid, Paris, Prague, Vienna, Milan, and Warsaw, but also two small ones, namely Liege and Saarbrucken.

The distinction between polygonal and star shaped Intersections can have interesting policy implications. The former allows to consider more distributed HSR infrastructures, with smaller stations along the polygonal perimeter, or with one main hub at the centre of it connected by public transport to the cities. The latter identify mandatory crossing points, implying that the HSR infrastructure must be integrated into the urban fabric or in its immediate vicinity, potentially increasing construction costs and complexity.

The recent work by Bruno (2022) on air-rail competitiveness, allows to draw a comparison between the hubs from a service and infrastructural point of view. Figure 47 shows the global hub potential obtained from the product between incoming and outgoing frequencies, thus how much each city is served by rail. Some of the hubs in Figure 46 (i.e., Paris, Vienna, Zurich) confirm their centrality not only given the infrastructure but also in terms or services. Interestingly, other hubs (i.e., Prague, Nuremberg) show great infrastructural potential but are less served, while Berlin for example ranks high in service level but not on the infrastructural side. This comparison could further spark a discussion on the benefits of making service level and infrastructural design interact between one another, and what could be the downside of excluding the former in terms of frequencies, different passenger flows and finally different appraisal and investments.

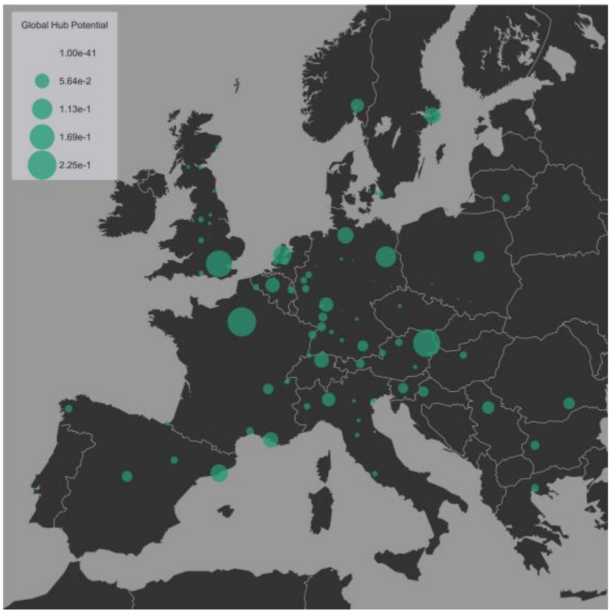


Figure 47 - Global Hub Potential (Bruno, 2022)

5.2.4 Common Budget Implications

The creation of a common budget to centrally manage common challenges is nothing new. The European Union's budget works in a similar fashion to the assumption made for this work. Each year, based on periodical agreements (MMF)(European Parliament, 2023), countries allocate funds to the EU, mainly proportional to their Gross National Income. The EU then has the power to redistribute these funds based on its priorities and investment plans, by never exceeding the annual contribution ceiling. Most of the major contributors receive significantly less than what they have contributed to, with funds being allocated especially towards nations with less developed economies (European Union Budget, 2023).

Within the modelling framework, the allocated budget plays an important role in determining the speed of investment. The higher the budget the more candidate links can be built per year. With the assumptions stated in Section 3.2, different budget allocation structures, as for example giving all the money to the model at the beginning or at predefined time steps, does not impact the iterative evolution. This is attributed to the static evolution of the economical parameters in the scenario, and wider economic effects of investments on the labour market, construction market and general economy are not accounted for. If this would have been the case, a certain a level of complexity and interdependency between the budget allocations and the broader economic context would have existed.

Secondly, Figure 38 showed how some countries contribute more than what they receive back in terms of infrastructural investments. Furthermore, some countries contribute more and do not have any economical gain from it, with negative national BCRs. Therefore, to develop a centrally managed investment, it could be considered to eliminate these countries from the budget contribution schemes and increase the budget contributions of the remaining participating countries and thus potentially decreasing their national BCRs. Or, at the same time, compensative measures can be proposed to all countries with negative BCRs, to address other strategic fields within these nations. These are deemed necessary to convince all countries, especially the ones that do not achieve benefits, to participate to such common infrastructural expansion plan.

Lastly, the case study national contribution of 0.07% of the GDP, has increased the network length by 13200 km, from the initial 10900 km extension. This shows that the goals of the 2011 European transport white paper of tripling the HSR network by 2050 are far from achieved, as found also by the European Court of Auditors (European Court of Auditors, 2018). Given the accumulated delay, and that it takes on average 15 years to build a line (European Court of Auditors, 2018), the investments in HSR should be significantly revised and improved to reach the 2050 goals. This is in line with the recent findings by the study commissioned in Germany (Deutsche Bahn et al., 2023), which also implies that the current network expansion strategies of the TEN-T networks should be improved with additional lines for a proper metropolitan coverage. The same opinion is also shared by the rail industry leaders, whose report (Ernst & Young, 2023) highlights how achieving the 2050 goals would require a quadrupling of the existing network. These considerations suggests that the current budget expenditures are not enough to meet the desired European HSR transport goals. Therefore, new strategies must be explored in this regard, especially concerning the creation of collaborative planning and investment, public-private partnerships, and innovative financing techniques such as infrastructural funds or market based infrastructural bonds.

5.2.5 Influence of Initial Network Configurations

In Section 5.1, the evolution of the modelling scenario starts from an initial base network of existing infrastructure, meaning that travel utility is already distributed following predefined patterns. Hence, the network evolution is influenced by an initial structure, which leads to a specific investment sequence. For the analyses of this Section, the modelling framework of Chapter 3 has been used to generate an alternative network structure starting from a base network with no existing HSR infrastructures. The goal is to understand how the model potentially behaves with no initial influence.

The first notable difference concerns how the network is designed and expands. Figures 48, 49 and 50 compare the model's evolution of the no HSR infrastructure case and the obtained scenario for France, Spain and Germany.

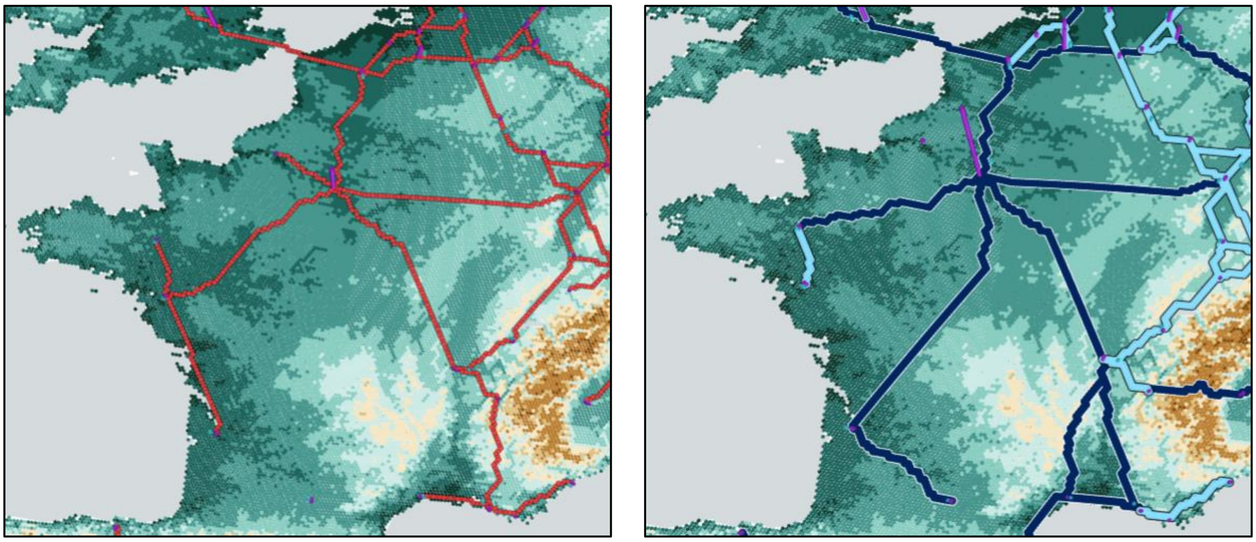


Figure 48 - Design comparison France: No base network on the left, obtained scenario (5.1) with existing (dark blue) and future infrastructure (orange) on the right

For France, different design alternatives can be seen for the radial lines towards Nantes and Marseilles. In the case of no initial infrastructure, t-shaped connections with peripheral areas, which than expand along the perimeter, are preferred to multiple direct lines from the centre to the outside. This improves the efficiency of the investment allocations.

For the Spanish case something similar can be observed. The Lisbon to Madrid infrastructure scores higher returns on investment if Seville is included as intermediate station, showing the trade-off between slightly higher travel times, and connecting a bigger demand basin with the same infrastructural spending.

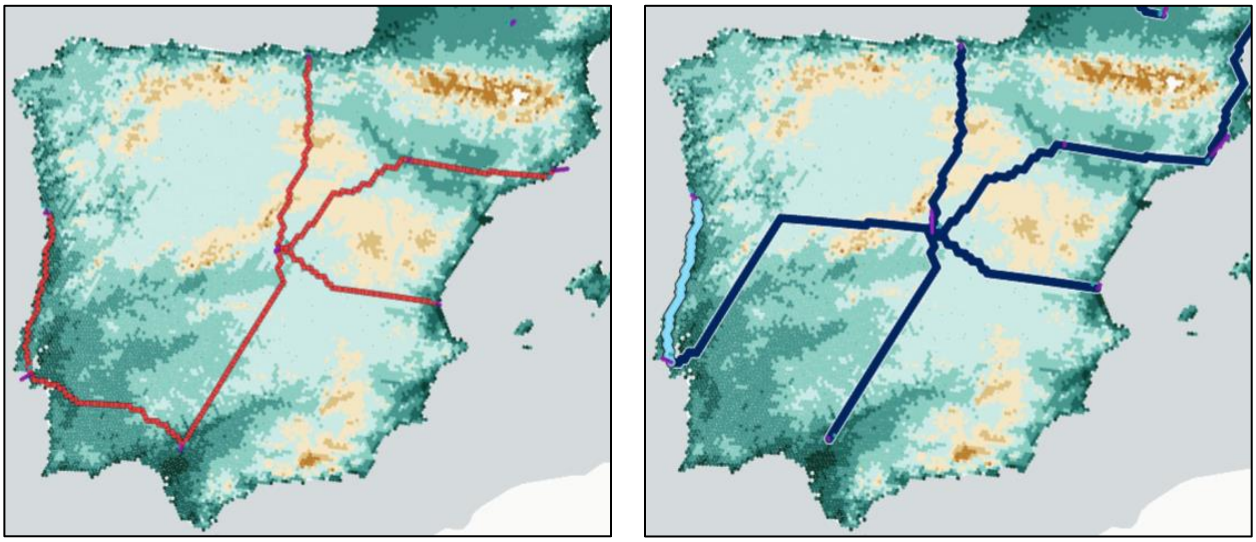


Figure 49 - Design comparison Spain: No base network on the left, obtained scenario (5.1) with existing (dark blue) and future infrastructure (orange) on the right

In the case of Germany, differences can be seen on the Munich to Berlin line, which is modelled as more economically feasible via Dresden and Prague, instead of via Leipzig and Nuremberg. In this case the model chooses the option which has the best trade-off between demand and travel times, investing in a corridor with bigger urban hubs regardless of the border implications. Furthermore, Berlin and the Ruhr area are connected via Hamburg, so to better capture demand from Denmark, instead of passing trough Hannover.

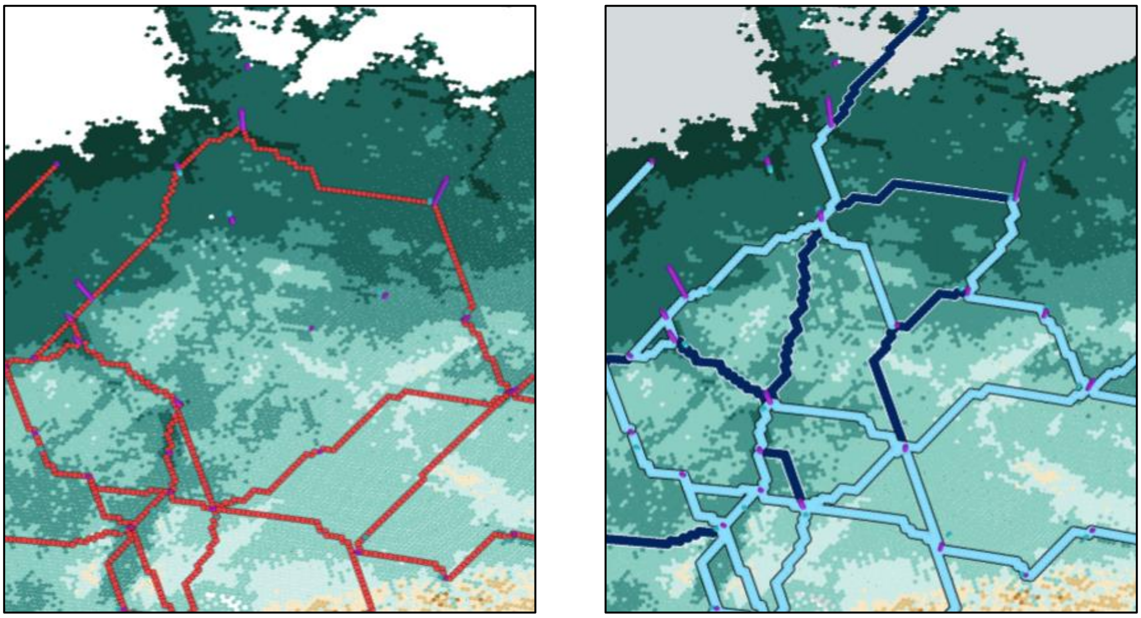


Figure 50 - Design comparison Germany: No base network on the left, obtained scenario (5.1) with existing (dark blue) and future infrastructure (orange) on the right

Different designs can be obtained also for specific lines, especially concerning cross-border connections. Figure 51 provides a snapshot of the network evolution without an initial base (left) and with an initial infrastructural configuration (right dark blue). The white circles on the left side of the images denote all the cross-border infrastructural differences between the two cases. Most of the lines are missing, such as the Barcelona-Montpelier, Turin-Lyon, Trento-Innsbruck (Brenner tunnel), Copenhagen-Hamburg (Fehmarn tunnel) and Rail Baltica projects. At the same time, two connections that can be found on the left side are not modelled for the existing base network case on the right. These are the Munich-Prague and Ljubljana-Trieste links.

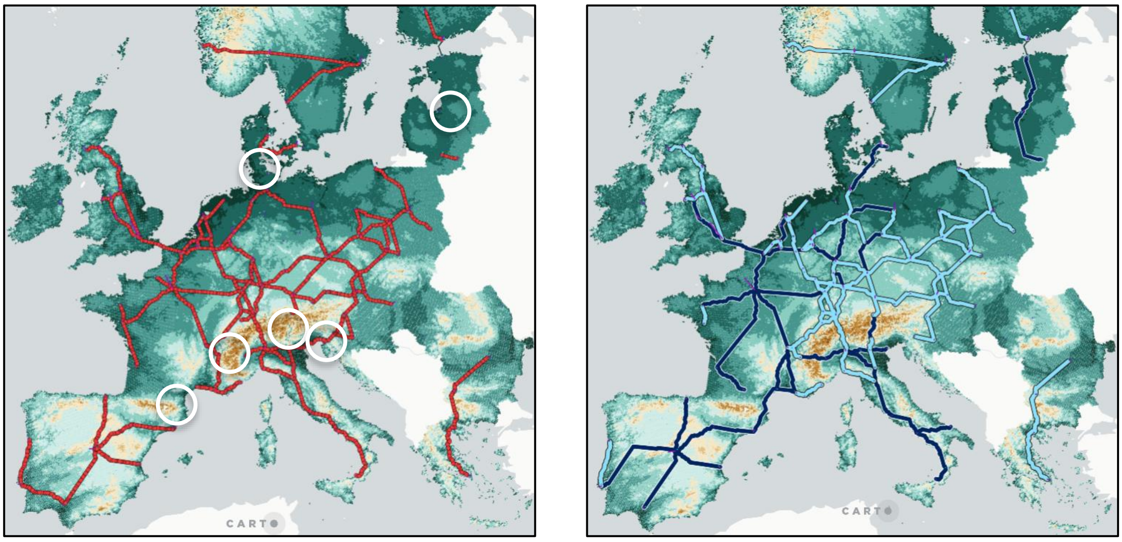


Figure 51 – Evolution scenarios with no base network (left), with base network specifications(Section 5.1)

Similarly, to the previous comparison of Section 5.2.1 with the TEN-T expansion plans, the fact that most cross-border connections are infeasible if not included in the base network can suggest that the model is incomplete. It appraises these connections as economically unfeasible due to high infrastructural costs (e.g., Turin-Lyon, Innsbruck-Trento) or low demand volumes (e.g., Rail Baltica, Hamburg-Copenhagen) that overpower limited benefits. The latter are not sufficient to compensate cost because of excluding induced demand, alternative speed and line design, or wider economic benefits. These would be in line with the solution adopted for the actual real cases (e.g., TEN-T policies), where the aforementioned infrastructures serve a variety of purposes to increase their utility, from mixed passenger-freight service (Rail Baltica, Brenner tunnel, Turin-Lyon) to road traffic (Fehmarn tunnel). Thus, a more complete model is expected to perform better in regard to cross-border connections.

Special attention should be also given to parameters already included, which might be inaccurate or wrongly set. For example, a mis calibrated trip distribution for cross-border connections, together with the exclusion of induced demand, could reduce passenger volumes and the impact of network effects. Further attention should also be given to corridor formation, appraisal, and elimination. For the latter, further experiments could be done by removing the constraint of a positive BCR and analyse if the profitability increases again after negative investments.

In conclusion, existing infrastructure can significantly affect the iterative patterns of the investment scenarios. The presence of an existing network impacts how new lines are planned, developed, and integrated, potentially prioritizing expansion and extensions of existing lines to enhance connectivity, showing significant path dependency and preferential attachment. At the same time, an existing configuration reduces the efficiency of the subsequent investments, especially if the base network has been constructed in a sub-optimal way. Therefore, exiting infrastructure can both facilitate and constrain the iterative patterns, requiring scenario analysis to understand how each scenario's evolution impacts ridership, economic effects, and overall project success.

5.2.6 The Potential of a Centrally Coordinated Decision Making Process

The scenario obtained in Section 5.1, assumes a central decision making process not influenced by any national appraisal framework. By considering all options and including cross-border Sections, the planning process can be enhanced, and better resource allocations can be achieved.

To explain this graphically, Figure 51 highlights the different decisions the model takes when considering a national (a), cross-border (b) or European (c) perspective in the case of the Netherlands. In all three scenarios existing infrastructure is operational. For the first image (a) the model is applied under the Dutch borders' constraints, obtaining the construction of the Amsterdam-Utrecht-Eindhoven connection. In the second case (b), where the model is allowed to explore the potential of connecting with neighbouring countries, two infrastructures are built: The Antwerp to Brussels link and the connection between Amsterdam and the Ruhr area via Utrecht. This means firstly that a link outside the Netherland (Brussels-Antwerp) is more beneficial to the country than any other infrastructure, and secondly that connections with urban hubs outside the national borders (Ruhr) yields significantly higher returns for the Dutch appraisal process than links within the country (Eindhoven) itself. Finally, in the last figure (c), the connections of the reference scenario (Section 5.1) concerning the Netherlands are presented. In this case the resource allocation is further enhanced by considering the bigger European picture. The investment sequence shows that the Brussels-Antwerp link is still a fundamental connection, but this time Amsterdam is connected to the Ruhr via Liege and Aachen. If this might seem to be less beneficial in terms of travel times, it actually improves the connections between Amsterdam and southern Europe, specifically towards Stuttgart, Zurich and Milan. Hence, the infrastructure is able to serve more demand while minimising costs and increasing travel times for certain OD pairs (e.g., Amsterdam-Ruhr) within an acceptable time frame.

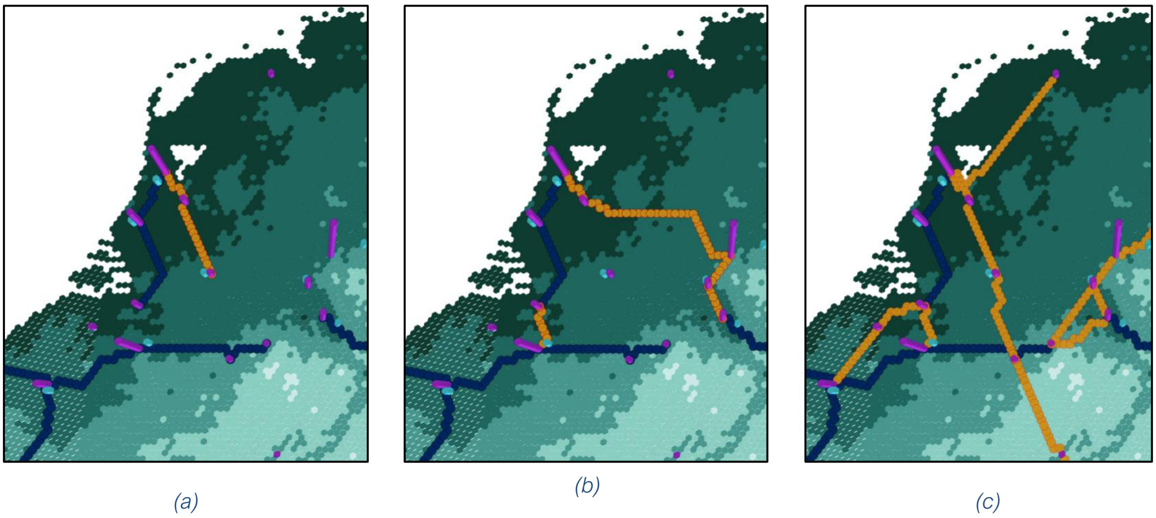

(a) (b) (c)

Figure 52 - Network evolution under national (a), cross-border (b) and European (c) perspective

Figure 51 thus highlights the relationship between efficient investment allocation and a comprehensive wide-ranging appraisal process. Considering a broader European perspective is thus more beneficial in terms of investment allocation, because is allows the model to have a more comprehensive view over demand flows and thus to estimate benefits over a wider range. This is also in line with the analysis carried out in Section 5.2.5 on the impact of an initial network configuration, which shows that more efficient designs could have been obtained by starting from an empty base network. This suggests that the existing European infrastructure, which has been built based on national appraisal and investment process, is not the optimal from a European point of view.

Further implications of a shared appraisal process can be seen in Figure 36 under the scenario results. There it is also shown that countries without investments in HSR on their territory benefit in terms of travel time and externality savings from the investment in neighbouring countries. This means that having an overall appraisal process that goes beyond national borders, allows to fully grasp spill-over effects and benefits that would have been otherwise excluded. Although the latter do not account for significant amounts, it is possible to enhance them by including further attributes in the appraisal process, such as wider economic benefits, connectivity improvements, and cross-border passenger and freight induced traffic.

Another important aspect of resource allocation is ensuring a more equitable distribution of wealth. By allocating funds to sections with high potential but limited economical spending power, such as the Kaunas to Vilnius or Bucharest-Sofia-Thessaloniki-Athens connections, transportation networks can contribute to reduce regional disparities and promote economic development. As already discussed in Section 5.2.4, challenges arise when attempting to convince multiple countries to allocate their budgets to improve HSR connections in territories that do not directly benefit them. This limitation necessitates careful negotiations and cooperation among nations to foster cross-border connectivity and ensure a cohesive cross-border transportation network.

In conclusion, having a centralized appraisal and investment process with a comprehensive overview of all countries involved, contributes to a more efficient, effective, and equitable HSR network expansion. This allows to account for spill-over effects between countries, improve cross-border connections, and design the network with an effective resource allocation. Therefore, by addressing the complexities related to multi actor management, it would be thus possible to increase both the effectiveness of investment allocation and the equity of investment distribution, facilitating economic growth, reducing disparities, and enhancing connectivity for the benefit of all involved regions.

5.3 Discussion of Limitations

The experiments, conducted in this study, are representative of reality but are influenced by necessary assumptions and simplifications due to time and computational constraints, impacting the quality of findings and the ability to address the research question, thus leading to discussions and recommendations on research limitations which may involve improvements or expansions. Assumptions

Concerning the investment allocations, this thesis assumes a central actor managing the decision making process of all countries involved in the case study, by collecting and allocating funds for different projects. This is one of the most challenging limitations to the study because it implicitly assumes that countries are willing to collaborate, invest in a common fund and agree to spend national budgets for investments which are not directly benefitting them. Furthermore, infrastructural projects are also a powerful political tool, thus an impartial and centralized decision making process seems far from being achieved. Nevertheless, other strategies can be explored, as for example a stronger funding mechanism where central authorities could detain more decision making power. Furthermore, it is recommended to develop plans that both outline the benefits and the costs of participating in projects of this scale, and that envision compensative mechanism to address disparity in budget allocation.

Regarding the modelling develop din Chapter 3, one of the main limitations is the level of detail of the infrastructure modelling. The current hexagon size of 6 used to model the terrain is considered insufficient for this purpose. With an average distance between centroids of 6km it is almost impossible in most of the cases to describe valleys or peaks in mountain ranges, therefore the model rarely builds a tunnel. Smaller hexagons would indeed prove to be a very effective way to model terrain, in order to have a better understanding of the costs as well as of the routing but. A second limitation regarding the modelling concerns the corridor formation and appraisal. For some corridors, the generated benefits are greater than the costs, thus justifying the economical feasibility of the investment. Usually, these are composed by a series of links with high demand potential, especially the ones close to big node, and links with low demand potential. Although the overall corridor BCR score is positive, the model invests firstly in the link with high potential, whose BCR is higher than the corridor one, and secondly it analyses the links with lower economical potential. In most of the cases, the latter have a BCR score lower than 1, as they might be considered for investments only if together with stronger links within a corridor. Therefore, one of the limitations that can be considered for the model, is related on how the final BCR score is considered. This implies a long-term strategic consideration, based on the trade-off between economical profitability and societal gains in terms of modal shift towards HSR. If a BCR maximization strategy is adopted, the benefits of building corridors may not be fully exploited but the final investments would be optimized. At the same time, considering corridors with a positive BCR over better performing single links, might reduce the return on investment but could contribute to significantly improve ridership and increase modal shift towards HSR.

A further consideration can be done regarding the trip distribution methodology adopted, which considers barriers such as country borders, languages, and Schengen area. As already mentioned in Section 3.3.3 regarding the exclusion of federal barriers, HSR has the potential to reduce distances not only on a geographical level, but to integrate different societies, cultures, or job markets closer together. In this sense the consideration of country borders could become obsolete, especially within the Schengen Area. For HSR corridors within dense regions such as the Amsterdam to Paris connection, borders are already an imperceptible barrier which is not significantly felt by travellers coming from the Netherlands and crossing Belgium towards France. In conclusion, based on the juridical and economical considerations, different parameters for trip distribution could be further explored, in order to better account for cross-border trips and not underestimate demand on these sections.

Assuming an infrastructure free of its capacity constraints can be a limitation with significant impact on the appraisal process. HSR investments allow to free up capacity on conventional lines for other service typologies, including regional, suburban and freight traffic. These benefits could guide the model to identify and prioritize bottlenecks, as well as investing in lines where improving freight movement would increase economical output and reduce congestion. Furthermore, the modelling of infrastructural capacity could introduce the trade-off between upgrading or building new infrastructure, allowing for a more precise cost estimation and the study of the effect of different speeds.

Finally, the biggest limitation considered for this study addresses the service side of HSR. A limitation of this study lies in the simplified approach to travel decisions within each mode, primarily relying on weighted travel time without considering travel costs and comfort, which are vital factors in real-world modal choices. Future research should explore incorporating these parameters to create a more accurate representation of travel behaviour. This could reveal significant impacts on modal splits, particularly for long-distance travel where low-cost carriers have influenced choices. Additionally, assessing comfort factors, such as the convenience of having a car during vacations or the ability to work while traveling, could provide valuable insights. Other aspects like safety perception and environmental awareness justify consideration in future studies, along with examining ticket prices to better understand competition between conventional rail and high-speed rail for short-distance trips and refine mode share analyses for various origin-destination pairs. Furthermore, throughout the modelling process, a static approach has been employed for demand, encompassing both trip generation and induced demand. The exclusion of dynamic parameters, especially at the local level, represents a limitation. Induced demand remains particularly challenging to estimate accurately in the context of high-speed rail (HSR). However, recognizing its potential as a game-changer for evaluating cross-border sections or links with substantial travel time improvements, it's imperative to delve deeper into induced demand. Moreover, considering infrastructural capacity constraints and analysing frequency changes could yield insights into induced demand, making it advisable to explore these parameters in the service layer of HSR.

06

Conclusions

Iryo, private high-speed rail operator participated by Air Nostrum and Trenitalia, Spain

6 Conclusions

In conclusion, this work developed an iterative network growth model to study the sequential evolution of the European HSR network as a result of the dynamic interaction between travel time improvements, demand distribution and infrastructural costs. The obtained model allows to bridge the gap identified in the literature by combining three main features:

1. Identifying a strategic sequential HSR investment plan towards the creation of a unified European HSR network, providing more insight for all stakeholders identified
1. Providing a detailed modelling of the infrastructure, as a result of a geospatial indexing of the topological features of the terrain
2. Further exploring the potential of iterative network growth models within the framework of a continental wide case study

In the following chapter, the obtained results are analysed in relation to the research questions in Section 6.1. Finally, the recommendations for the stakeholders and for future works are given in Section 6.2 and Section 6.3.

6.1 Research Questions

In this Section, the research questions introduced in 1.6 are presented and answered.

Question 1: Which is the sequence of high-speed rail investments that could lead to the creation of a unified European HSR network, while minimizing costs and increasing benefits ?

The first sub-research question is the opening statement towards the insights produced by this work and answers the main research question. The sequence of high-speed rail investments that could lead to the creation of a unified European HSR network while minimizing costs and increasing benefits given a yearly budget of 12.5 billion euros, has been presented in Section 5.1. The evolution strategy envisions 13000 km of new lines to be build between 2023 and 2065, with significant expansion potential for countries such as Germany, Poland, Czech Republic, Switzerland, the United Kingdom, and Austria. The existing network coverage is further densified in Central and eastern Europe, as well as in the Benelux area and northern Italy. Finally, the emergence of peripheral long-distance HSR connections is modelled, such as between Athens and Bucharest, Stockholm and Bergen, Stockholm and Gothenburg, and between Lisbon and Porto.

The obtained link construction sequence provides thus a clear and step-by-step investment plan to achieve a unified European HSR network given current conditions. It illustrates where, when and at what cost potential lines could be built, because of the dynamic interaction between travel time improvements, demand distribution, and investment costs, whose evolution has been modelled over time.

Question 2: What are the impacts of a potential unified European HSR network in terms of infrastructural costs, travel time utilities and externality savings ?

The completion of the sequential investment plan presented in Section 5.1 would require a total present investment of 269 billion euros, divided into yearly budget allocation of 12.5 billion euros. The increased interconnection and mobility capacity introduced by the new HSR infrastructure would lead to present benefits of 834 billion euros, divided into 604 billion for travel time savings and 230 billion for externality savings. In conclusion, given the costs and the benefits of such network evolution, the final benefit to cost ratio score is 3.1, highlighting the significant economical gains of the proposed investment plan on a European level.

Section 5.1 further shows the implications of a unified European HSR network on the case study countries, highlighting the existence of major budget contributors and investment receivers, of countries achieving a positive return on investment and countries that don't. This leads to the discussion on whether to eliminate countries with negative national Benefit-Cost Ratios (BCRs) from budget contribution schemes, or to introduce compensative measures to foster participation and address disparities.

In modelling terms, the proposed investment plan highlights how the relationship between infrastructural specifications and benefits leads to the identification three infrastructural use case designs: Short investments improving connectivity and thus passenger volumes, connections improving travel time over longer distances, and infrastructural investments improving both at the same time in case of network densification.

Question 3: How would the modal split of the European long-distance transport market be impacted by the creation of a unified European HSR network ?

The sequential investment plan of Section 5.1 forecasts the increase of rail's mode share from 12% in 2038 to almost 27% in 2065. Once all infrastructural investments have been completed, 136 million trips from air and 112 million trips from car can be diverted towards the rail network.

Additionally, the correlation depicted in Figure 40, relating mode share to travel distance, unveils a shift in rail and air competitiveness, marking a transition from around 300 km in 2023 to approximately 600 km in 2065. This signifies a crucial transformation where journeys within this range will predominantly favour rail travel, redefining the long-distance transport landscape.

In modelling terms, findings in Figure 39 highlight the importance of cross-border and cross-network connections in increasing the utility of previously separated network configurations. The observed correlation between sudden increases in rail mode share and the establishment of such links underscores their strategic importance in fostering a well-connected and efficient rail network across nations. This insight reinforces the overarching goal of establishing a cohesive and sustainable European high-speed rail system, wherein cross-border collaborations act as catalysts for improved transportation modes and enhanced connectivity.

Question 4: To what degree does a national or European appraisal process affect the investment sequence of high-speed rail links ?

As discussed in Section 5.3, a broader appraisal process could significantly impact the outcome of the investment decisions on a national level. By considering the Netherlands, it has been demonstrated that a national, cross-border or European wide appraisal process implies three different investment alternatives, with the latter improving the resource allocation due to a broader and comprehensive demand modelling ability. The same has been witnessed when running the model under different initial network configurations, suggesting that a holistic and borderless approach to appraise infrastructure could lead to more optimal resource allocation when compared to current infrastructure. Furthermore, the analysis of generated benefits for the countries of the case study demonstrates the existence of spill over effects across borders, which, if enhanced with precise modelling techniques and parameters, could play a decisive role in the appraisal process.

In economical terms, a European appraisal process also has significant implications on the budget contributions, investment allocations and benefits experienced by each country. Results reported in Section 5.1 identify major contributors and major receivers, finally dividing participating nations between the ones that have economical gains from the shared investment plans, and the ones that don't. This highlights the need for compensative measures to achieve a cohesive investment plan aligning with the diverse needs of European nations.

Finally, by addressing the equity within the investment processes, a unified and centralized decision making process would allow to improve the investment distribution also among countries which lack the proper funding tools but that still show great potential in terms of HSR ridership, generating benefits for all countries involved. In conclusion, a structured and centralized appraisal process with a holistic overview of demand patterns also across border, could facilitate a comprehensive evaluation of both direct and indirect benefits, enabling more informed investment decisions and fostering cross-border connectivity.

Question 5: What are the key considerations that can be drawn from the infrastructural expansion towards the creation of a unified European HSR network?

The infrastructural expansion towards a unified European HSR network is characterised by the dynamic interplay among passenger demand, travel time enhancements, and infrastructure expenses. This iterative progression unfolds in three distinct phases following the principles of preferential attachment: starting with the establishment of links between key urban centres, then expanding to connect networks across greater distances, and ultimately focusing on densifying regions with residual potential for improvement. However, the application of preferential attachment is notably constrained by edge profitability, which reflects the delicate balance between spatial considerations (i.e., infrastructural costs and travel time benefits) and node attributes (i.e., passenger demand). This dynamic is evident in the initial phase, where the model prioritizes independent connections unrelated to the existing network due to their high BCRs.

Path dependency plays a significant role in the appraisal and iterative process of candidate investments. Utility patterns are heavily influenced by previous decisions and historical infrastructure, as demonstrated by the differences in network evolution between scenarios with and without initial HSR infrastructure. Cross-border connections stand out as pivotal points that unlock network expansion, underscoring their capacity to eliminate discontinuities and amplify the attractiveness of rail transport.

This paper introduces an innovative approach for understanding and enhancing transportation networks through sequential decision-making processes. Unlike global optimization methods, which can be resource-intensive and lead to non-local solutions, these iterative growth models provide a more realistic approach that accommodates practical budget constraints and avoids the complexity of substantiating comprehensive global decisions. The study thus highlights the importance of studying and implementing sequential approaches to network improvement due to their practical feasibility and potential to address inefficiencies effectively.

6.2 Recommendation for Stakeholders

In the following Section, the conclusions and results are reviewed to formulate recommendations for the stakeholders considered in Section 1.4.

6.2.1 European policymakers

To improve the current investment and governance practices towards the creation of unified European HSR network and overcome the coordination issues identified (European Court of Auditors, 2018), the following recommendations are formulated for the European policy makers.

The establishment of centralized appraisal process is seen as the main requirement to improve the investment efficiency and have a comprehensive understanding of demand flows, benefits, and spill-over effects across the European landscape. Centralized appraisal allows to increase investment effectiveness with improved infrastructural designs and recognize the significance and benefits of cross-border connections to stimulate collaboration on projects that extend beyond national boundaries. In this regard it is recommended to explore the adoption of a share but independent infrastructural investment fund with proper spending power, by setting minimum contribution requirements for the member states, and measures to compensate negative returns on investments with country tailored infrastructural investments.

A break with the past and towards a new beginning is needed in terms HSR infrastructural plans policies and historical budget allocation trends. This is considered paramount for the achievement of the 2050 goals. If the same budget allocations trends are kept, a shared European appraisal process is not implemented, and proper coordination among countries is not achieved, it is highly unlikely that such targets are met. In practical terms, the following improvements are recommended:

- Revise current infrastructural plans by providing a detailed yearly planning and construction timeline, together with clear responsibility and budget allocations
- Update appraisal guidelines by including mandatory EU wide appraisal
- Create an independent decision making body with responsibility over infrastructural appraisal, funding, and construction, similarly to the European Union Agency for Railways.

6.2.2 European rail industry leaders

Considering the recent interest for the topic by the rail industry leaders (Ernst & Young, 2023; Deutsche Bahn et al., 2023), the following recommendations are given.

The creation a unified European HSR network requires the cooperation among multiple actors especially between European and national institutions. Rail industry leaders, representing interest of many different countries, can act as a bridge between all political stakeholders involved, facilitating the integration towards a single decision making process. It is therefore paramount that the rail industry guides with its knowledge the political entities to the adoption of the most beneficial practices in terms of infrastructure modelling and appraisal.

For this purpose, it is recommended to further study the deployment of iterative network growth models within business cases, accompanied by a holistic European appraisal process. This would allow have a better understanding of the underlying dynamical interaction between appraisal parameters, initial network configurations and path dependency mechanisms. In this regard, the evolution from densely populated centres towards investments with diminishing returns, as well as connections designs with different function need to be accounted for. Furthermore, explore the use of hexagonal indexing systems to improve the accuracy and detail of current infrastructural modelling practices. For the latter, despite the low level of detail, the methodology has proven to be very effective for parametric design estimation and precise infrastructural cost calculations.

Secondly, the results and modelling methodologies presented in this thesis could serve as a foundation for further research within the rail industry consulting sector. By refining modelling parameters, incorporating consistent demand models into the iterative evolution process, and showcasing the insights derived from modelling outcomes, a novel advisory approach could be integrated into the services portfolio. This expansion opens up opportunities beyond the rail industry, extending the model applicability to areas like power grid analysis and the development of sustainable policies.

6.2.3 Scientific community

With relatively few works addressing the topic of iterative evolution in the context of the European HSR network, this work has formulated a novel methodology using the work by Donners (2016), Grolle (2019) and Cats et al. (2021) as main reference. The recommendations for the scientific community are mainly three.

The iterative network growth model presented provides significant insights on how the interaction between the considered parameters affects the evolution and investment choices in the long run. Specifically, this work identifies the dynamic interplay between passenger demand, travel time enhancements, and infrastructural costs. Regarding this methodology it is recommended to further improve the modelling dynamics by including the service level design. This would allow to account for a series of parameters excluded in this work, such as frequencies, infrastructural capacities, prices, comfort attributes and induced demand. The iterative evaluation process could thus be enhanced by modelling the sequential interaction between infrastructural supply and service provision. In this sense, future works could further develop this methodology based on Donners (2016) for the demand assessment, on Grolle (2020) for the line design and frequency setting, and on this work for the infrastructure modelling. Overall, the development towards dynamically integrating infrastructural specifications and service attributes could provide a comprehensive modelling technique with great scientific potential to address transport network expansion problems and designs.

Within the modelling practices, link and corridor formation, appraisal and elimination need to be further explored. These three steps significantly affect the sequential investment results, by including or excluding potential candidate alternatives. In this regard, the corridor appraisal process plays the biggest role. In this regard, it is recommended to explore and formulate a novel appraisal standard, which could justify the construction of corridors over links also if the latter could be more beneficial over certain Sections.

Finally, the hexagonal geospatial indexing system is a promising modelling technique with incredible potential. It is recommended to explore higher resolution values to properly exploit the ability of detailed indexing. Given the cost underestimations and distance over estimations encountered in this work, higher level of detail could lead to improved results. Furthermore, it is suggested to explore the possibility of including additional parameters within the indexing framework, such as land-use or aggregated population data.

6.3 Recommendation for Future Research

The iterative network growth model presented in this work has been formulated based on a set of assumptions that could be further relaxed to improve the modelling process. The following paragraphs present a set of recommendations for future works, touching upon the most

The first recommendation for future research concerns the terrain modelling. The level of detail chosen to discretize the topological features of the terrain, as well as the land use assumptions, heavily impact the ability of the model to calculate accurate infrastructural corridors and relative costs. If adequate computational power and accurate data sets are available, it is thus suggested to increase the level of detail to higher resolutions. Not only elevation calculations would be enhanced but land use patterns can be considered as well. This in turn would allow to have more accurate cost modelling, as well as to consider different land use specifications (e.g., natural areas, urban settlements) and constrain the infrastructural expansion avoiding real life obstacles. Furthermore, a better discretization could improve the modelling of urban areas, allowing to expand the infrastructural analysis also to stations and the integration of HSR infrastructure within urban networks and areas.

Secondly, the assumptions regarding the utility formulation can be relaxed to include additional utility parameters and accurately model travellers' choice over long-distance transport. Specifically, travel costs (e.g., ticket price, fuel prices) ad comfort parameters (e.g., working while travel, privacy, connectivity) can more accurately reproduce real-case travel patterns and improve the accuracy of the mode choice modelling.

The modelling of the service provision and of the infrastructural capacity can also be considered among the recommendations for future work. This would allow to model the relationship between existing services, infrastructural costs, and potential new services. For example, existing rail lines with relatively low traffic could be upgraded for higher speeds, whereas busier corridors would be better off with new HSR infrastructure that could increase capacity on conventional lines for both regional and freight trains. Including these parameters would therefore allow to achieve a higher level of detail regarding line design, which would allow to include different alternatives in addition to purely HSR dedicated lines for speed of 250km/ or above.

Regarding the appraisal process used in this model, it can be improved by considering additional parameters for the benefit and costs calculations. High-speed rail investments have been proven to impact a wide range of factors, including land use, labour markets, regional GDPs, accessibility patterns, industrial clustering, and innovation. These positive or negative influences, if included, would significantly impact the results of the appraisal process by introducing a more holistic approach for the consideration of benefit and costs.

Finally, by considering the different modelling parameters, special attention for future works must be given to the corridors' construction, specifically for the link creation and the k-shortest path alternatives. In this regard, determining distance thresholds for direct connections can significantly affect utility generation and appraisal outcomes, determining the evolution patterns of the network. For example, it can be explored how to create corridors between urban areas that have a high attraction potential, or along a set of cities that has high political and economical influence. Furthermore, modelling alternative routes between OD pairs might include unrealistic options, exclude important transit hubs, or return redundant connections. For the latter case it would be interesting to explore the adoption of k-shortest paths formulations with limited overlap.

07

Reference

Thalys cross-border high-speed rail service on the Amsterdam-Brussels-Paris corridor
Netherlands, Belgium, and France

References

Agency for Railways. (2020). European Union. Fostering the railway sector through the European Green Deal

Aparicio, A. (2016). Exploring recent long-distance passenger travel trends. 6th Transport Research Arena April 18-21, 2016

Bacares, C., Brunel, J., & Sigaud, D. (2019). Influence of the evolution of high-speed railway infrastructure on the success of Italian liberalization. Competition and Regulation in Network Industries, 20(2), 113–137. https://doi.org/10.1177/1783591719847615

Barabasi, A., & Albert, R. (1999). Emergence of scaling in random networks. Science, 286 (5439), pp. 509 - 512, Cited 26753 times. DOI: 10.1126/science.286.5439.509

Barrón, I., Campos, J., Gagnepain, P., Nash, C., Ulied, A., Vickerman, R., & de Rus, G. (2009). Economic Analysis of High Speed Rail in Europe.

Black, W. (1971). An iterative model for generating transportation networks.

Branković, N., Kalem, A. (2021). Infrastructure costs and benefits of European high-speed rail

Campos, J., de Rus, G., & Barron, I. (2007). The cost of building and operating a new high speed rail line. University Library of Munich, Germany, MPRA Paper.

CARTO. (2023). carto.com

Cascetta, E., & Coppola, P. (2014). High Speed rail (HSR) induced demand. EWGT2013 – 16th Meeting of the EURO Working Group on Transportation

Cascetta, E., Cartenì, A., Henke, I., & Pagliara, F. (2020). Economic growth, transport accessibility and regional equity impacts of high-speed railways in Italy: ten years ex post evaluation and future perspectives. Transportation Research Part A: Policy and Practice. Volume 139. Pages 412-428. ISSN 0965-8564. https://doi.org/10.1016/j.tra.2020.07.008.

Cats, O., & Birch, N. (2021). Multi-modal network evolution in polycentric regions. Journal of Transport Geography, 96:103159-. doi: 10.1016/J.JTRANGEO.2021.103159

Cats, O., Vermeulen, A., Warnier, M., & van Lint, H. (2020). Modelling growth principles of metropolitan public transport networks. Journal of Transport Geography, 82:102567. doi: 10.1016/J.JTRANGEO.2019.102567

CE Delft (2019). Sustainable Transport Infrastructure Charging and Internalisation of Transport Externalities: Main Findings.

Chorus, C. G. (2010). A New Model of Random Regret Minimization. European Journal of Transport and Infrastructure Research, 10(2). https://doi.org/10.18757/ejtir.2010.10.2.2881

Community of European Railways. (1989). Proposals for a European High-Speed Network.

Copernicus. (2023). Land Monitoring Service. EU-DEM v1.1. https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1

Creel, J., Holzner, M., Saraceno, F., Watt, A., & Wittwer, J. (2020). How to spend it: A proposal for a European Covid-19 recovery programme. The Vienna Institute for International Economic Studies (wiiw).

de Bortoli, A., Bouhaya, L. & Feraille, A. A life cycle model for high-speed rail infrastructure: environmental inventories and assessment of the Tours-Bordeaux railway in France. Int J Life Cycle Assess 25, 814–830 (2020). https://doi.org/10.1007/s11367-019-01727-2Der

Deutsche Bahn, & PTV group. (2023). Metropolitan network: a strong European railway for an ever closer union.

Dijkstra, E.W. (1959). A note on two problems in connexion with graphs. Numer. Math. 1, 269–271. https://doi.org/10.1007/BF01386390

Ducruet, C., & Lugo, I. (2013). Structure and dynamics of transportation networks: Models, methods and applications. 347-364.

EIB. (2009). Sapin: EIB finances Madrid-Valencia high-speed line. https://www.eib.org/en/press/all/2009-040-spain-eib-finances-madrid-valencia-high-speed-line

Ellwanger, G., & Georger O. (2001), 'The impact of social and demographic changes on transport demand in Europe in the year 2030',Rail International, Association Internationale du Congrès des Chemins de Fer (AICCF), 6 (6-7), 139-147.

Ernst & Young (Ernst & Young). (2023). Smart and affordable rail services in the EU: a socio-economic and environmental study for High-Speed in 2030 and 2050.

Eurocontrol. (2022). EUROCONTROL Data Snapshot #30 | EUROCONTROL. https://www.eurocontrol.int/publication/eurocontrol-data-snapshot-30-daily-utilisation-aircraft-type

European Commission. (2011). White Paper. Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0144

European Commission. (2013). Mobility and Transport. Trans-European Transport Network (TEN-T). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013R1315

European Commission. (2014). Guide to Cost-Benefit Analysis of Investment Projects. Economic appraisal tool for cohesion policy 2014-2020. https://wayback.archive-it.org/12090/20221203224508/https:/ec.europa.eu/inea/sites/default/files/cba_guide_cohesion_policy.pdf

European Commission. (2018). Comprehensive analysis of the existing cross-border rail transport connections and missing links on the internal EU borders. Study commissioned to KWC

European Commission. (2019). European Green Deal. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

European Commission. (2020a). Sustainable and Smart Mobility strategy. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789

European Commission. (2020b). Long-distance cross-border passenger rail services. Study contract MOVE/2020/OP/0013 European Commission commissioned to Steer and KWC. https://op.europa.eu/en/publication-detail/-/publication/34244751-6ea3-11ec-9136-01aa75ed71a1

European Commission. (2021). Statistical Pocketbook. EU transport in figures

European Court of Auditors. (2018). European high-speed rail network: not a reality but an ineffective patchwork.

European Environment Agency. (2008). European Mountain Areas dataset. https://www.eea.europa.eu/data-and-maps/data/european-mountain-areas

European Parliament. (2023). Multiannual financial framework. https://www.europarl.europa.eu/factsheets/en/sheet/29/multiannual-financial-framework

European Rail Agency. (2023). ERA's vision, mission, values and tasks

European Union Budget. (2023). https://www.europeanunionbudget.eu/#!

Eurostat. (2019). Glossary: price level ndex (PLI). Glossary:Price level index (PLI) - Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Price_level_index_(PLI)

Eurostat. (2020). Key figures of European Transport. 2022 Edition. Key figures on European transport – 2022 edition (europa.eu)

Eurostat. (2023). Population projections in the EU. https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=497115#:~:text=The%20EU%20population%20is%20projected,to%20419.5%20million%20in%202100.

Finger, M., Montero, J., & Serafimova, T. (2022). Towards a smart and sustainable single european transport area. Florence School of Regulation. Robert Schuman Centre. https://cadmus.eui.eu/bitstream/handle/1814/74731/Towards_a_Smart_and_Sustainable_Single_European_Transport_Area.pdf?sequence=1&isAllowed=y

González-González, E., Marsden, G., & Smith, A. (2010). How important are environmental factors in the case for High-Speed Rail? A comparison of the United Kingdom and Spain.

Goeverden, C. D., & van Arem, B. (2010). Background Factors Explaining Train Choice in European Long- Distance Travelling. In Proceedings WCTR 2010 (pp. 1–18). Lissabon: Instituto Superior Técnico

Gutiérrez, J., González, R., & Gómez, G. (1996). The European high-speed train network: Predicted effects on accessibility patterns. Journal of Transport Geography. Volume 4, Issue 4. Pages 227-238. ISSN 0966-6923. https://doi.org/10.1016/S0966-6923(96)00033-6.

Holzner, M., Heimberge, P., & Kochnev, A. (2018). A ‘European Silk Road’. Research Report 430. The Vienna Institute for International Economic Studies (wii).

Holzner, M., Weber, K., Zahid, M.U., & Zangl, M. (2022). Environmental Impact Evaluation of a European High Speed Railway Network along the ‘European Silk Road’. The Vienna Institute for International Economic Studies (wii).

HS2. (2023). HS2 project update. https://www.hs2.org.uk/what-is-hs2/hs2-project-update/

Infrasite.nl. (2023). HSL-Zuid. https://www.infrasite.nl/glossary/hsl-zuid/?gdpr=accept&gdpr=accept

IRICAVDUE. (2023). https://veronapadova.it/

IRJ. International Rail Journal. (2022). Infrastructure. Spanish government plans €2.5bn link from Bilbao to Santander. https://www.railjournal.com/infrastructure/spanish-government-plans-e2-5bn-link-from-bilbao-to-santander/

Kortazar, A., Bueno, G., & Hoyos, D. (2021). Dataset for the life cycle assessment of the high speed rail network in Spain. https://doi.org/10.1016/j.dib.2021.107006.

Kouwenhoven, M., de Jong, G., Koster, K., van den Berg, V., Verhoef, E., Bates, J., & Warffemius, P. (2014). New values of time and reliability in passenger transport in The Netherlands. https://doi.org/10.1016/j.retrec.2014.09.017.

Levinson, D., & Yerra, B. (2005). The emergence of hierarchy in transportation networks.

Nash, A. (2007). Europe's High-Speed Rail Network: Maturation and Opportunities.

NetowrkX. (2023). Network Analysis in Python. https://networkx.org/

OECD. (2016). High Speed Rail Competition in Italy. A Major Railway Reform with a “Win-Win Game”?

OECD. (2023). Functional urban areas by country. https://www.oecd.org/regional/regional-statistics/functional-urban-areas.htm

Open Route Service. (2023). https://heigit.org/tag/api-en/

Ortúzar, J.D., & Willumsen, L.G. (2011) Modelling Transport. 4th Edition, Wiley, Hoboken.

Pablo-Martí, F., & Sánchez, A. (2017). Improving transportation networks: Effects of population structure and decision making policies. Scientific Reports. 7. 10.1038/s41598-017-04892-2

Park, Y., & Ahn, S. B. (2010). Optimal assignment for check-in counters based on passenger arrival behaviour at an airport. Transportation Planning and Technology, 26(5), 397–416. URL https://www.tandfonline.com/doi/abs/10.1080/03081060310001635887

Peters, J. Han, E., Kumar, A. Peeta, S. & DeLaurentis, A. (2014). Incorporating High Speed Passenger Rail into a Multimodal Network Model for Improved Regional Transportation Planning.

Queensland Government. (2011). Introduction - Cost-benefit analysis manual road projects

Rail Baltica. (2023).About rail Balica. https://www.railbaltica.org/

Ramjerdi, F. (2010). Value of time, safety and environment in passenger transport – adjusted to NTM6. Technical Report I.

Reuters. (2020). Watchdog blames UK government for high-speed rail cost overruns | Reuters. https://www.reuters.com/article/uk-britain-railways-idUKKBN1ZN003

Ross, J. (1994). High-speed Rail: Catalyst for European Integration?

Rouhani. (2019). Transportation Project Evaluation Methods/Approaches. https://mpra.ub.uni-muenchen.de/91451/1/MPRA_paper_91451.pdf

SAGA. (2023). url: https://saga-gis.sourceforge.io/saga_tool_doc/2.2.0/shapes_grid_0.html

Spiegel. (2010). Germany spends billions on the wrong rail project. https://www.spiegel.de/international/germany/stuttgart-s-white-elephant-germany-spends-billions-on-the-wrong-rail-project-a-717575.html

Steininger, B.I., Groth, M. and Weber, B.L. (2021), "Cost overruns and delays in infrastructure projects: the case of Stuttgart 21", Journal of Property Investment & Finance, Vol. 39 No. 3, pp. 256-282. https://doi.org/10.1108/JPIF-11-2019-0144

Sui, Y,. Shao, F., Sun, R., Li, S. (2012). Space evolution model and empirical analysis of an urban public transport network. Physica A-statistical Mechanics and Its Applications, 391(14):3708-3717. doi: 10.1016/J.PHYSA.2012.01.011

UIC. (2015). High-Speed Rail Fast track to Sustainable Mobility. https://uic.org/IMG/pdf/high_speed_brochure.pdf

UIC. (2018). High-speed rail around the world. Historical, geographical and technological development

UNECE. (2021). Trans-European Railway High-Speed. Master plan study. A general background to support further required studies. Phase 2

UNECE. (2021). Trans-European Railway High-Speed. Master plan study. Phase 1

Vickerman, R. (1997) High-speed rail in Europe: experience and issues for future development. Ann Reg Sci 31, 21–38. https://doi.org/10.1007/s001680050037.

Witlox, F., Zwanikken, T., & Jehee, L. (2022). Changing tracks: identifying and tackling bottlenecks in European rail passenger transport. Eur. Transp. Res. Rev. 14, 7 (2022). https://doi.org/10.1186/s12544-022-00530-9.

Xie, F., & Levinson, D. (2007a). Modelling the Growth of Transportation Networks: A comprehensive review. Research Papers in Economics.

Xie, F., & Levinson, D. (2007b). Topological Evolution of Surface Transportation Networks. Social Science Research Network.

Yan, X., & Wang, M. (2009). Evolution of Public Transport Networks: An Empirical Analysis. 2644-2649. doi: 10.1061/41039(345)436

Roadmap Towards a Unified European High-Speed Rail Network

Filippo Borgogno

Department of Transport and Planning, Faculty of Civil Engineering and Geosciences (CEG), Delft University of Technology, Delft , Netherlands.

Keywords: High-speed rail, Long-distance travel, Europe, Parametric infrastructure design, Iterative network growth model

---

ABSTRACT

High-speed rail (HSR) is gaining increasing attention due to its sustainability and transport capacity, aligning with ambitious European transport goals for 2030 and 2050. Despite its potential, the creation of a unified European HSR network faces challenges rooted in poor coordination and national interests. This study addresses the absence of a comprehensive, long-term strategy for establishing such a network, with a specific focus on critical infrastructure development. It introduces an iterative network growth model to determine where, when, and at what cost HSR infrastructure should be built under centralized decision-making processes. The approach analyses the dynamic interaction between infrastructure expansion and the long-distance transport market demand distribution. Results emphasize the benefits of adopting centralized decision-making and appraisal processes, highlighting that achieving these goals requires a comprehensive, collaborative effort, as well as a proper European institutional investment management.

---

1 Introduction

In recent years, rail transport has gained significant attention in Europe for being safe, smart, and sustainable. The EU's funding and policy push for a unified European Railway Area is currently revitalizing rail's importance, but despite the efforts, rail's use is limited due to performance disparities with other modes, especially over cross-border connections. High-speed rail (HSR) offers a potential solution offering speed, accessibility, and sustainability advantages. Ambitious goals have been set and both industry leaders and policymakers are collaborating to build a comprehensive HSR network to meet the future expansion potential (European Commission, 2013; 2020). Yet, a unified European HSR network is facing multiple challenges from coordination issues between participating countries. Recent assessments of future and existing European HSR infrastructures have shown cost overruns, delays, and low quality financial management, which have led to a patchwork of poorly connected isolated networks (European Court of Auditors, 2018). The ongoing discussion has highlighted the pressing need for more efficient and collaborative approaches to establish a long-term investment vision. However, contrasts arise when establishing the right balance between preserving national autonomy and realizing a seamlessly interconnected European HSR network. These challenges continue to be central to establishing a unified and efficient trans-European high-speed rail network.

This study aims to bridge the knowledge gap regarding the absence of a comprehensive long-term strategy for establishing a unified European high-speed rail network. The primary research objective encompasses understanding where, when and at what cost to build high-speed rail infrastructure based on a centralized decision making process. Subsequently, the network evolution and the dynamic interaction between infrastructural expansion and the long-distance transport market will be further analysed. To address these research objectives, a novel methodology to study the network evolution with specific focus on infrastructure is developed.

By analysing comparable studies addressing these topics, two different lines of research are identified. Firstly, the scientific literature addressing the creation of a unified European HSR network is explored, and secondly, the scientific literature proposing modelling frameworks to map network evolution and its interaction with demand patterns is analysed.

Scientific research has extensively explored the ramifications of a European high-speed rail (HSR) network, examining accessibility, innovation, demand distribution, and service provision. Gutierrez et al. (1996) analysed railway accessibility patterns within the EU, identifying spatial disparities and the potential polarization towards urban hubs due to high-speed train introduction. Vickerman (1997) discussed initial national HSR network developments, highlighting challenges in network design, investment, and quality. Accessibility shifts towards major centres were observed, potentially affecting economic growth. Nash (2007) emphasized institutional barriers in achieving an integrated European HSR network, advocating for the resolution of national system independence issues for cohesive development. These studies collectively underscore the importance of accessibility, network integration, and overcoming institutional challenges for successful European HSR implementation.

Donners (2016) aimed to quantify the seating capacity potential of an integrated European Rail area beyond national borders. The methodology adopted employed the 4-step Transport Model, assessing potential trip demand, distribution, mode choice, and link line assignment in Europe. The results indicated a potential 22% increase (240 million trips) in trips, with the international trip share potentially rising from 6% to 25% (37% in a growth scenario). However, existing connections support insufficient service, with a 40% reduction in effectively offered seats, leaving 58.6 million international trips unserved. While proposing a first valid quantitative modelling of the European long-distance passenger rail market, it lacks service design and infrastructural considerations, assuming a fixed network structure for its analyses.

Grolle (2020) complements Donners' (2016) work by addressing service design within the context of high-speed rail (HSR). Using the Transit Network Design and Frequency Setting Problem (TNDFSP) for HSR, he analysed design variables, pricing, and governance strategies, obtaining a final line configuration with frequencies. Centralized governance and external cost internalization improve HSR market share (from 14.7% to 29.9%) and the societal cost-benefit ratio (by 20.0%). The study emphasizes the need to integrate overlapping and cross-border lines and highlights conflicts between national and international interests. However, like Donners' work, the author doesn't delve into the economic implications of infrastructural investments, assuming a fixed network structure for its analyses.

The EU-RAIL study (Ernst & Young, 2023) envisions a European HSR master plan to link major cities, projecting benefits of 750 billion euros against a cost of 550 billion euros. It employs shock scenarios to forecast demand changes, conducting a Cost-Benefit analysis based on the 2030 and 2050 TEN-T core and comprehensive network goals. However, the study lacks specificity in network connections, country-specific parameters, and a proposes a static network configuration for chieving the goals.

The PTV Group study, commissioned by Deutsche Bahn (2023), explores a European HSR network's topological configuration. Using a travel demand model, it predicts growth in transport demand due to population, prosperity changes, and travel time enhancements. The analysis reveals that existing infrastructural expansions based on TEN-T corridor characteristics fall short of EU targets. Meeting these levels by 2050 would require a metropolitan network with 21,000 km of new lines. However, like previous studies, the demand assessment exceeds infrastructural expansion details, relying on the fixed TEN-T corridor network configuration.

Other studies on the topic have been proposed by Holzner et al. (2018) who explored the concept of a European Silk Road, envisioning two 11,000 km transport corridors to connect western and eastern Europe, Russia, and the Balkans. Creel et al. (2020) proposed Ultra Rapid Train lines across major European cities and the western Balkans, totalling 16,600 km of new lines at a cost of approximately 1.1 billion euros. Following the approach of Holzner et al. (2018), both studies suggest pooling resources in a publicly owned limited company, in line with European recommendations.

The works conducted by UNECE Studies (2017, 2021), The United Nations Economic Commission for Europe, examined the potential of a Trans-European Railway network to connect eastern urban regions with western Europe. UNECE's latest report (2021) identified HSR corridors based on international criteria, analysed missing links and bottlenecks, and conducted Cost-Benefit Analysis (CBA) to gauge network impact. This study's emphasis on a corridor approach for efficiency, use of UIC-based cost values for infrastructure, and identification of an investment schedule distinguishes it. While studies like Holzner et al. (2018) and Creel et al. (2020) present intriguing investment propositions, a lack of rigorous scientific support for corridor choices raises questions. UNECE's research (2017, 2021) stands out with its methodical identification of HSR corridors, analysis of missing links, CBA, and investment schedule. A collective trend toward public ownership and alignment with European recommendations is evident, but no study has been found that addresses the step by step investigation of how to achieve European HSR network development goals.

By shifting focus towards the evolution of transportation networks, it becomes clear that this process involves dynamic changes driven by socio-economic, technological, and environmental factors, practically referring to infrastructure expansion, connectivity shifts, and modal choices. Understanding this evolution is crucial for effective planning and management. Different strategies exist to model network growth. Xie and Levinson (2007a) highlight five categories: transport geography, optimization, transport network growth models, economics of network growth, and network science. Unlike optimization models, transport network growth models focus on underlying dynamics. They analyse interactions between transport demand, spatial constraints, policies, and infrastructure development. These models offer insights into adaptation and emergent properties. Given this study's aim, the focus will be on iterative transport network growth models coupled with transport geography and network science concepts. This approach supports long-term planning and policy decisions.

Further early transport network growth models include Black (1971) and Levinson and Yerra (2005). Black's diffusion-oriented model simulates investment based on profit relative to costs, avoiding small angles in network expansion. Levinson and Yerra's model examines road hierarchies' emergence through iterative speed improvements. Although it addresses upgrades, it highlights investment's role in network evolution. Both models utilize decentralized investment rules.

Xie and Levinson (2007b) propose an interurban road evolution model emphasizing interaction's impact on network hierarchy formation.

Peter (2014) presents LUCIM, evaluating high-speed rail potential in a multimodal system, considering energy, demographics, economy, ridership, and the related impacts. While inspiring for macroscopic interaction modelling, Peter's fixed network configuration limits optimal solution exploration. In conclusion, these models shed light on investment-demand dynamics, hierarchy emergence, and multimodal interactions, aiding transportation planning and understanding trade-offs.

Pablo-Marti et al. (2017) examines towns' spatial distribution impact on transport networks and connection enhancement decisions. Their iterative model involves cities expressing improvement preferences based on minimum spanning trees from Dijkstra's algorithm. The central decision maker considers these choices with equal or population-proportional voting power, leading to an investment decision strictly influenced by path dependency. Initial network states yield varying evolutions, driven by population and link potential. The study advocates decentralized iterative design for realism and efficiency. This innovative approach models network evolution through dynamic city interaction and parameters, holding potential as a reference for similar studies.

Cats contributes to iterative network growth discussions with two studies. The first (Cats et al., 2020) employs iterative cost-benefit analysis to evaluate transport mode investments based on travel time savings versus infrastructure costs in a monocentric urban public transport network. Dynamic population distribution functions highlight evolving network dynamics, from early expansion to core densification. Notably, a strong population-network topology link is underscored, yet assumptions of monocentricity and mode-independent analysis are limitations. The second study (Cats et al., 2021) advances to polycentric urban regions and multimodal networks. A 4-step demand model informs an iterative investment model, promoting best-scoring candidates from Benefit-Cost ratio perspectives, considering expansion, densification, and frequency enhancement. The research outlines network configurations for diverse polycentric urban layouts, reaffirming population-network correlations. However, limitations include the absence of spatially informed infrastructural cost analysis and the requirement for new links to connect with the existing network, impacting network evolution realism.

The analysis of the literature revealed two main research gaps in relation to the coordination issues in achieving a Trans-European HSR Network. Firstly, all studies reviewed assume a fixed network configuration to be achieved either in 2030 or 2050, excluding dynamic evolution. Furthermore, none of the studies delves into a comprehensive examination of infrastructural costs, particularly with regards to the influence of spatial implications.

The objective of this study is thus to develop a sequential long-term HSR sequential investment plan under the assumption of a centrally managed decision-making process. Furthermore, the main focus is the network evolution based on a detailed infrastructural analysis.

To address the objective of this study, an iterative network modelling framework is developed, following the approach adopted by Cats et al. (2021). A novel iterative growth model is formulated, which generates the potential infrastructural solutions, analyses their impact on travel demand distribution and builds the most beneficial candidate based on the trade-off between benefits and costs. This allows to iteratively adapt the network expansion to the evolving demand distribution, investment costs and resulting network structures.

The following Sections present firstly the iterative network growth model and its formulation (Section 2). Subsequently, the experimental set-up for the European Union is outlined and explained (Section 3). The results from the model's application are then analysed and discussed (Section 4). Finally, the main conclusions and suggestions for future research are formulated (Section 5).

2 Modelling Framework

The proposed modelling framework comprises three modules (Figure 1): Input Data, Base Network, and Iterative Growth. The Input Data module (Section 2.1) employs a hexagonal MICRO layer grid to represent Europe's topographical features, while the MACRO layer grid identifies potential rail connections based on city importance and serves as a foundation for the physical infrastructural design provided by the MICRO grid.

The Base Network module (Section 2.2) initializes transport demand distribution and modes' utilities using Donners' (2016) 4-step model formulation.

In the Iterative Expansion module (Section 2.3), potential high-speed rail (HSR) links are incrementally added to the existing network, evaluated for passenger demand, and assessed in terms of benefits and costs. The best-scoring link based on Benefit-Cost ratio (BCR) is added to the base network if it complies with the budget constraints. Finally, the base network is updated, and the model can iterate again.

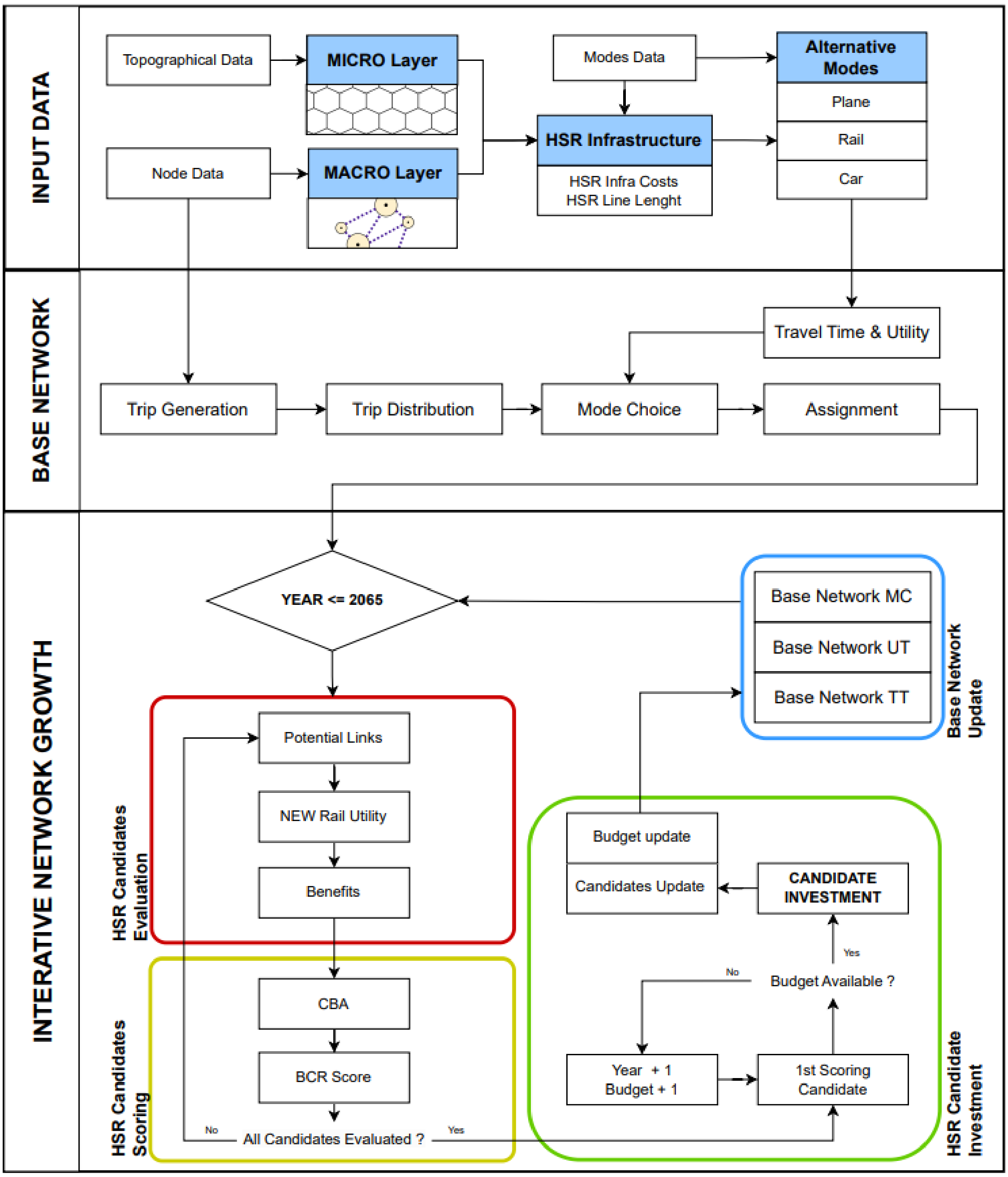


Figure 1 - Iterative Growth Model Workflow

2.1 Input Data Module

The Input Data module aims at generating the necessary data components for the model. Specifically, it provides the modelling of the geographical area and of the HSR infrastructure, respectively through the MACRO and the MICRO layer grids (Figure 2). The former is responsible for establishing which potential rail links are feasible in terms of connectivity, while the latter models the topographical characteristics of the geographical area taken into consideration.

Combined, they return the specifications for existing and potential high-speed rail lines in terms of travel time, investment cost and distance. This process resembles the methodology adopted by Yerra et al. (2005), of adopting one layer for the road network and one layer for the land use layer.

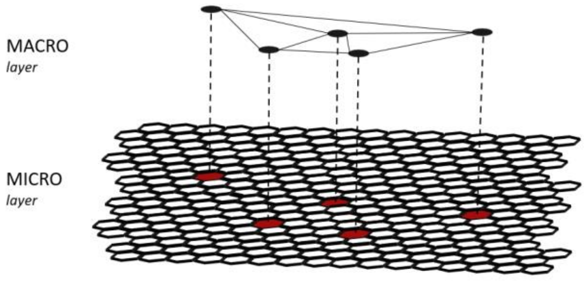


Figure 2 - Topological (MACRO) and topographical (MICRO) representation of the spatial configuration

2.1.1 MICRO layer

The MICRO layer represents the topographical structure of the special configuration. The H3 library is used to divide the geographical space considered into a grid of hexagons with predefined areas, based on the level of detail desired. This allows to perform highly detailed analysis of large spatial data sets (Uber, 2018). Furthermore, it is possible to discretize space and represent all associated characteristics and parameters trough the hexagons' centroids. The final geographically indexed hexagons are then processed to add country specifications and remove sea hexagons. Finally, topographical characteristics are added in the form of altitude values, obtained with using QGIS in combination with DEM (Digital Elevation Model) raster from Copernicus. Subsequently, the neighbours of each hexagon are identified in order to establish which connections among centroids are feasible, leading to the creation of a proper grid structure.

To consider the topographical variations, represented by the elevation changes between hexagons, a novel approach based on terrain layering is introduced. This methodology enhances the hexagonal representation by incorporating additional layers at predefined heights that depict the hexagon's elevation composition. Therefore, the hexagonal grid can be expanded beneath the surface, incorporating underground elements, creating a transition from 2D to 3D hexagonal structure (Figure).

Therefore, nodes are allowed to link each other horizontally, upwards, or downwards, so to replicate real life-high-speed rial lines as presented in Figure 5. Therefore, the elevation difference between layers determines the steepness of the diagonal edges between nodes on different layers, as obtained by dividing the changes in elevation by the horizontal distance between nodes. Therefore, the elevation difference must be carefully defined based on the gradient's requirements.

Terrain layering allows assigning distinct cost weights to surface and underground nodes. Hexagonal centroids indicate costs for building HSR infrastructure through surface or underground areas they represent. Defining costs per centroid is intricate due to various influencing factors. The European Court of Auditors (2018) highlights project uniqueness, political pressures, coordination issues, and design variations. Natural obstacles further complicate matters. Three key factors impacting HSR costs emerge from scientific literature (Campos et al., 2007; UNECE, 2022; Barron et al., 2009): terrain, population density, and project design. Terrain shape significantly impacts costs, with mountains raising expenses. Population density influences land costs, whereas design choices, like gradients and structures, also play a role.

To compute the final cost per kilometre, a cautious approach considering available data is therefore crucial. Moreover, data available pertains only to a limited group of countries with existing HSR networks, making cost predictions for future infrastructure in other nations more uncertain. To address this, the work introduces a two-step methodology. Initially, average construction costs per kilometre are derived for the entire case study, considering both surface and underground infrastructure. These averages are grounded in literature data from existing projects. Subsequently, a cost weight (W_i) is calculated for country (i), based on four key factors: Percentage of rough terrain (T_i), population density (D_i), national GDP (GDP_i), and Price Level Index (PLI_i). These parameters are scaled against the case study averages, and their mean results in the national cost weight (1):

$$W_i = \overline{\left(\frac{T_i}{Terrain} + \frac{D_i}{Density} + \frac{GDP_i}{GDP} + \frac{PLI_i}{PLI}\right)} \qquad (1)$$

For each country, the cost weight is then multiplied by the average surface and underground construction costs found previously, returning national specific infrastructural parameters.

With the costs per kilometre in place, the centroids of surface or underground nodes can be initialized. Then, based on the connection between neighbours, the weight of the edges in the MCIRO layer grid are defined, by weighing the costs values of the two centroids each edge is connecting, multiplied by the distance between centroids (Figure 3).

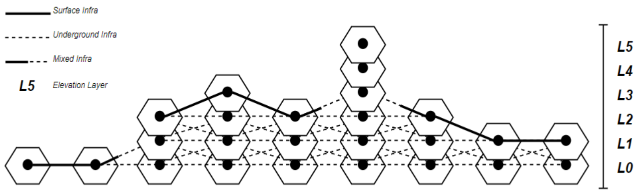


Figure 3 - Three-dimensional MICRO grid

Other than the gradient, design factors such as curvature radius, signaling systems, and urban line design are not considered. For sea infrastructure, comprising bridges and tunnels, a distinct methodology is employed. These unique projects are manually modelled due to their specialized nature and usually limited number. Feasible sea stretches are analysed and the hexagons representing them are added to the MICRO layer with elevation 0 and corresponding costs.

2.1.2 MACRO layer

The MACRO layer mimics demographic distribution and maps the potential rail connections across urban hubs. Major population centres become nodes, connected by rail links as edges. Similar to hexagons, nodes are geographically indexed and paired with the nearest hexagon of the MICRO layer grid, encapsulating attributes of the represented centre.

Nodes are key urban hubs selected based on Donners' (2016) formulation, considering population, local GDP, and higher education. The parameters associated with each node are population, GDP per capita, and coordinates, along with language, country, Schengen area presence, federal systems, country population, surface, and city density.

Having defined MACRO nodes, the subsequent step is initializing edges that connect them. Unlike prior studies referencing mainly TEN-T policies (Donners, 2016; Grolle, 2020; Ernst & Young, 2023; Deutsche Bahn, 2023), this thesis pioneers a novel rail link methodology without predefined schemes. The approach relies on cities' influence range, gauged by population, GDP per capita, and country's urban density ratios. A weighted influence measure is calculated, squared to moderate outliers, and multiplied by a predefined distance parameter, d, to determine influence radius (2):

$$Reach_i = \sqrt{\frac{P_i * \ GDPpc_i}{\text{Urban Density}_c}} * d \qquad (2)$$

The formulated equation links cities when overlapping influence circles touch, where the sum of radii ($Reach_i$ + $Reach_j$) equals or surpasses city distance. Careful calibration of distance parameter d is vital: high values yield excessive links, while low values might exclude connections, requiring a balance to prevent undue complexity. Influence radius determines the model evaluation horizon and connection potential. The edges of the MACRO layer grid represent only rail links, assuming that other modes (car, plane) are unrestricted and travel directly from origin to destination, while trains navigate nodes. Thus, this method generates a (MACRO) grid of potential rail links.

2.1.3 *HSR Infrastructure Construction*

By combining the MICRO and MACRO grids, the ultimate HSR infrastructure is derived. This combines the city connections and the three-dimensional topographical terrain modelling into a single layer. The process unfolds as follows: First, an existing conventional rail link is identified from the MACRO layer grid. Second, Dijkstra's weighted shortest path algorithm (Dijkstra's, 1959) identifies the sequence of hexagons linking city coordinates through centroids. Lastly, this path returns both the total infrastructural costs, in terms of the sum of edges' weights, and the infrastructure's length, given by the number of hexagons times the to centroid distance.

2.2 Base Network Module

The second modelling phase initializes the transport demand patterns for all OD pairs, forming the initial transport scenario serving as base for the Iterative Growth module. The Base Network step outlines mode performance (car, plane, rail), excluding buses.

2.2.1 *Weighted Travel Utility*

The Base network module calculates travel utilities to compute mode choice. These are assumed to depend solely on travel time as the primary disutility parameter. Trips between ODs are modelled as direct for car and air, while rail uses the MACRO layer grid edges to traverse the network. For the latter, the Base Network module also initializes existing HSR connections by improving travel times on those specific Sections.

Additionally, to in-vehicle time, the utility calculation of a trip considers also access, egress and waiting time for each mode. Waiting or access times vary, with planes involving security checks and rail offering better access to centrally located hubs for example. The utility of each of these stages is then weighted to reflect perceived disutility, based on the values adopted by Grolle (2020), as presented in Table 1.

	Access	Waiting (h)	Exit Waiting (h)	Egress
Weight	1.36	1.5	1.5	1.36

Table 19 - Trip stages utility weights

2.2.2 *4-step Trasport Demand Modelling*

The approach adopted is taken from Donners (2016) who applied the 4-step transportation modelling framework to the European long-distance transport passenger market. The first stage, trip generation, computes annual trips generated by a city accounting for long-distance vs. shorter trips and incorporating Functional Urban Areas (FUAs) to capture commuting zones (OECD, 2023). Each FUA's attraction equals production, accommodating two-way travel symmetry. Trip generation is obtained by multiplying each node's population with the average European yearly trips, and the ratio between each city's per capita GDP ratio against the case study mean, reflecting income's impact on travel willingness.

In the second stage, trips generated are distributed across metropolitan areas using Donners' (2016) gravity model, that accounts for travel barriers such as language and Schengen borders. Federal barriers are omitted considering HSR's potential to bridge distances. Additionally, the Donners' formulation is transformed into a doubly constrained gravity model, to ensure that all generated trips are distributed. Socio-economic adjustment factors, friction, attraction, and production factors are iteratively balanced to reach convergence and obtain trip distribution

The Random Regret Minimisation (RRM) choice model (Chorus, 2010) is chosen for mode share calculations due to limited data requirements and its performance in capturing mode and route choices. Mode split is based on the difference in weighted travel utilities, input to the systematic regret, calculated using Logsum, and to the multinomial-logit formulation for final mode share.

Finally, trips are assigned based on an All-or-Nothing criterion, to reduce computational complexity.

2.3 Iterative Growth Module

The final module evaluates HSR lines through an iterative process that weights performance, costs, and economic feasibility. It calculates both NPV and BCR, invests in the candidate with the highest BCR, updates travel data and the base network for the next iteration.

2.3.1 *Corridor Construction*

Firstly, the iterative model expands direct city connections obtained for the MACRO layer grid into corridors using k shortest paths restricted by a time limit (Figure 3). This enhances infrastructural design options and accuracy by creating connections which include more cities along their path. Furthermore, it improves the evaluation of the interaction between demand distribution and infrastructure designs. Corridors are vital to reduce sub optimal result and considering network effects. The combination of direct links and corridors, thus terminates the creation of the candidate investment pool,

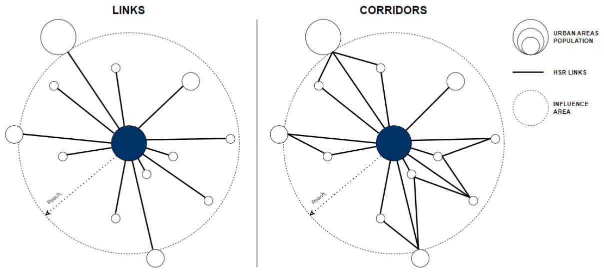


Figure 4 - Corridor creation process

2.3.2 *Candidate Investments Evaluation*

All candidate investments, comprising links and corridors, are evaluated based on the ability to attract existing demand due to improved travel times. Induced demand is excluded due to estimation complexity. The process involves initializing rail Sections with new HSR times, assessing impact on demand, mode choice and weighted utilities in terms of travel time and externalities savings. The evaluation thus returns the total time saved, the externality saved, and the total number of passengers affected by the infrastructural improvement.

2.3.3 *Financial Feasibility*

In accounting for travel time savings, the use of a single Value of Time (VOT) may not accurately reflect diverse national preferences and costs. To address this, the Price Level Index (PLI) is used to adjusts reference VOTs values to purchasing power differences between countries, enhancing the investment appraisal alignment to the cost estimations. National VOTs are then multiplied with the weights defined in Section 2.2.1 to obtain specific national VOTs for the different trip stages.

Considering externalities savings, they encompass reductions in air pollution, accidents, noise, and more. While often internalized through regulations or incentives, this work integrates externalities reductions into high-speed rail (HSR) investment appraisal as benefits. Grolle's (2020) categorization is used, which assumes equivalence in externalities between conventional and HSR modes. Externalities are not adjusted to any country index, as negative effects on the surrounding environment should count equally among nations.

The second phase assesses the financial feasibility of HSR candidates using Cost-Benefit Analysis (CBA). NPV and BCR are calculated by comparing monetary costs (infrastructure and maintenance) and benefits over time using cashflow calculations. To this end, an investment timeline is set, together with a fixed planning and construction period, and a predefined discount rate. Corridors' partial construction is considered, tracking evolution via a built matrix. NPV and BCR are used together for comprehensive project ranking, by using the former to rank alternatives for the same OD, whereas the latter is used to rank alternative projects on the case study level. This allows to build where there is the most return on investment, without being influenced by the national VOTs.

2.3.4 *Investment Decision & Network Update*

The best scoring HSR investment is chosen based on BCR and in line with budget constraints. Yearly budget is the sum of the countries' contributions, calculated as a share of the GDP, the latter obtained by analysing historical spending patterns of countries with HSR in within the case study. If no positive BCR is returned, the process stops. If the budget is not enough, the model iterates to the next year obtaining more budget. If budget is left, it is saved for the next iteration. Upon investment, edges are updated immediately so to be considered in the next iterations.

The final stage updates the base network, travel utility, mode choice, and candidate links. The chosen investment is removed from the candidate pool and all the OD pairs composing the investment are eliminated. Built links are marked active in the built matrix. Travel times are updated, mode share recalculated, and budget adjusted. This completes the iterative process, transitioning to the experimental set-up chapter.

3 Case Study: The Trans-European HSR Network

To evaluate the modelling framework proposed in the previous chapter, the concept of the trans-European HSR network is presented for the case study chapter. Section 3.1 introduces the general scope, Section 3.2 the input data module initialization, Section 3.3 the base network module initialization while Section 3.4 the iterative growth module initialization. Finally, Section 3.5 provides the base network configuration to be used in application of the modelling framework.

3.1 General Scope

HSR lines are defined as rail infrastructures with speeds higher than 220 km/h or 250 km/h, depending if an air alternative exists (UIC, 2018), based on the key modelling criteria of dedicated passenger lines. The timeline spans from 2023 to 2065, aligning with EU milestones for 2030 and 2050 and accounting for a 15-year construction period. Data is based on pre-COVID-19 statistics, and the study covers 28 countries in Continental Europe, including EU members, Norway, Switzerland, and the UK, while excluding Malta and Cyprus. Europe's diverse population density and terrain provide a valuable backdrop for assessing the model's behaviour concerning transport demand, cross-border links, and geographic factors. Additionally, many European countries lack HSR infrastructure, meaning that model outcomes have reference plans to be compared to and data is up-to-date and accurate.

3.2 Input Data Module Initialization

3.2.1 MICRO layer grid

To initialize the MICRO layer grid, a hexagon resolution level 6 is chosen for its balanced accuracy and computational efficiency. The geographical area is thus divided into 145,254 land hexagons (Figure 5), after excluding sea hexagons and areas outside the geographical scope.

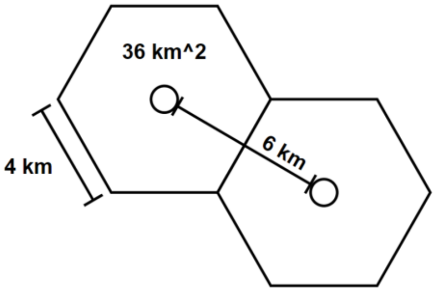


Figure 5 - Hexagon specification for resolution 6

Neighbouring hexagons are identified to determine potential edge connections, and a third dimension is added using Copernicus' DEM raster data (Copernicus, 2023), associating each hexagon's centroid with elevation values (Figure 6).

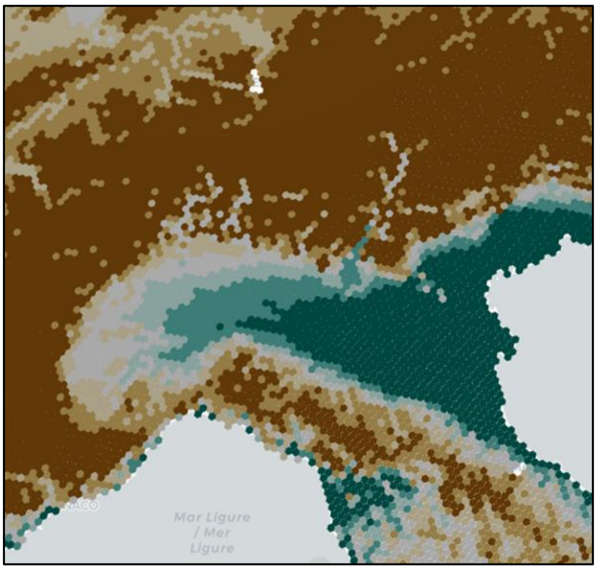


Figure 6 - Hexagonal elevation mapping

The hexagons are then layered based on an elevation gap of 250 meters, enabling a 3D representation of both surface and underground terrain. The resulting steepness gradient is 4%, in line with HSR design parameters (UIC, 2018). With the new representation, hexagons now account for 293258 units connected by 1,633,783 edges.

Average surface and underground HSR construction costs for the case study are established based on historical UIC cost data on existing infrastructure considering the percentage of tunnels and bridges (UNECE, 2022). This results in 19 million euros per kilometre for surface infrastructure and 55 million euros per kilometre for underground infrastructure, adjusted to current prices. Finally, average values are multiplied by country specific cost weights based on population density, terrain, PLI, and GDP per capita. The result aligns with the European Court of Auditors' cost estimations, yielding an average of 25 million euros per kilometre for surface infrastructure (European Court of Auditors, 2018). For sea infrastructure, cost values are added manually to the hexagons concerned. In conclusion, the edges are weighted by averaging the costs values of the two centroids they are connecting. In this way, surface, underground and partially underground infrastructural Sections and their costs are obtained. The latter represent tunnel entrances and tunnel exits.

3.2.2 MACRO layer grid

The MACRO layer grid selects 125 cities based on the findings by Donners (2016), with additional adjustments to exclude urban centres outside the geographical scope and include urban hubs that are strategic from a modelling perspective. Population data includes commuting areas defined by the OECD (OECD, 2023). The 450 connections obtained between cities depend on population, economic importance and urban density, balancing network connectivity and computational complexity (Figure 7).

Figure 7 - MACRO grid edges

3.2.3 HSR Infrastructure Specifications

By combining the MACRO and MICRO layer grids, Dijkstra's weighted shortest path algorithm (Dijkstra, 1959) is applied to determine HSR infrastructure routes, balancing cost, and distance, returning the length of all potential HSR lines and their investment costs.

A final validation of the infrastructure modelling is performed, comparing obtained results with existing infrastructure. Results show a 13% underestimation for the former and a 12% overestimation for the latter. Cost underestimations are mainly attributable to the level of detail, not enough to properly model terrain conformation and obtain the right amount of tunnels and bridges, causing cost underestimations and less direct connections.

3.3 Base Network Module Initialization

3.3.1 Travel time & Travel Utilities specifications

For the modes considered, the parameters presented in Table 2 based on regression analyses by Donners (2016) are used to calculate travel times and utilities.

	Speed (km/h)	Distance (km)	Detour Factors
Car	100	ORS	1.2
Plane	700	GCD	1
Conventional Rail	110	ORS	1.15
HSR	220	Own Calculations	1.09

Table 20 - Mode parameters for travel time and utility calculations

For HSR the distance has been already obtained, and assuming an average speed of 220 km/h it is possible to calculate travel time. Air distance is defined by the Greater Circle Distance, and with average speed of 700 km/h, travel time is obtained. Instead, for car travel times OpenRouteService (ORS) is used, adjusted with a detour factor of 1.2. Conventional rail is assumed to be equally influenced by spatial features as car, thus its travelled distance is divided by 1.2, multiplied by rail's detour factors and divided by an average speed of 110 km/h.

Additional trip stages are added to the travel time calculations. For air travel, waiting time includes 110 minutes of check-in and security procedures, 30 minutes for exiting from the airport, and access/egress times calculated using ORS for city-to-airport distances. Car travel adds a 10% penalty for pauses during the trip. Rail travel considers 15 minutes waiting time. City specific rail access/egress times are obtained from OECD FUA data based on urban surface, ensuring accuracy based on city locations and centrally located train station assumptions.

Finally, travel utility is weighted with the specific weight parameters per trip stage identified in Section 2.2.1, and used to compute mode choice.

3.3.2 4-step Transport Demand Model Initialization

The annual number of trips generated by each urban area is determined by multiplying the population by the ratio of the urban centre's GDP per capita against the case study average, and by a factor of 9 which assumes the average yearly trips of a European (Donners, 2016).

The revised trip distribution is initialized with the parameters accounting for language and border barriers from Donners (2016). Given that the author calibrated these under a different formulation and mainly for western Europe revealed data sets, recalibration is strongly suggested. Nevertheless, the new doubly constrained method results in a more balanced trip distribution. Some cities in Germany, the Netherlands, the UK, and Belgium underperform compared to the original model but are limited in the impact due to their initial high traffic volumes. At the same time, eastern and northern European cities and peripheral hubs such as Lisbon, Athens, and Tallin improve their previously underestimated traffic volumes significantly. Overall, the model enhances trip distribution equity among countries and city choices.

Mode choice relies on the parameters adopted by Grolle (2020), with β as -0.01 and μ as 1, and is determined by Logsum of weighted travel utility differences applied by the RRM choice model.

Finally, All-or-Nothing assignment is performed.

3.4 Iterative Growth Module Initialization

3.4.1 Corridor Construction Specifications

The k shortest path and time limit parameters have been obtained to at least reproduce all current infrastructures. For example, the creation of the corridor based on the direct link between Amsterdam and Paris, should include Rotterdam, Antwerpen, Brussels and Lille. This returns k equal to 20 and time limit equal to 1.3. Both parameters are then multiplied by the links travel time to find the upper bounds for the corridor creation.

3.4.2 Candidate Investment Evaluation & Financial Feasibility

The iterative network expansion begins with corridor evaluation, assessing travel time and externality savings benefits. This consists in iteratively updating HSR travel times for OD pairs and calculating the weighted shortest path. computing modal splits. Travel time savings are translated into monetary terms using country-specific values of time, initially based on values found for the Dutch market (Table 5)(Kouwenhoven, 2014; Grolle, 2020) and adjusted for other countries based on PLI. Furthermore, different trip stages are appraised by different VOTS to reflect the weights of Section 2.2.1.

(€/h)	PLI Index	VOT In-Vehicle	VOT Access/ Egress	VOT Waiting
Netherlands	1.17	58	79	87

Table 21 - Dutch VOTs for the different trip stages

Externalities like accidents, pollution, climate change, noise, congestion, habitat damage, and well-to-tank costs are considered in the benefit estimation, with cars incurring the highest costs. Tabel 4 presents the respective values (CE Delft, 2019).

(€-cent/pax-km)	Air Plane	Rail	Car
Total	4.28	1.3	12.1

Table 22 - Total Transport Externalities for the different modes

The financial evaluation involves calculating the Net Present Value (NPV) by discounting the annual cashflow, representing the difference between benefits and costs, over a 50-year investment lifetime and 15 years of construction (European Court of Auditors, 2018). These longer than usual values have been assumed based on recent HSR life-cycle assessments (Kortazar et al., 2021; De Bortoli et al., 2021) and on the consideration that HSR infrastructure are built with more modern technologies to last longer. Planning costs of 10% are allocated over the initial 8 years of construction, with 90% of the remaining investment allocated in the last 7 years (UIC, 2015; Barron, 2009). Periodic maintenance costs are estimated to be 0.3% of the total construction costs, to adjust to country specific market values (UIC, 2015). A 4% discount rate is applied (European Commission, 2014), and NPV and Benefit-Cost Ratio (BCR) calculations are conducted to rank candidates and investment alternatives.

The best-scoring corridor, offering the highest utility relative to costs, is selected for investment if complying with budget constraints. The GDP share obtained from historical investments in Spain, Italy, Germany and France is 0.07% of national GDP. By summing all countries contributions based on their GDP, the total budget available yearly for the iterative investment in infrastructures 12.5 billion euros.

3.5 Base network HSR configuration

The iterative model developed is applied in the context of the European HSR network, which already accounts for an existing structure in some countries. To this end, the Base Network is initialized with HSR travel times for dedicated lines that are in operation, under construction or received funding up to 2023. An exception is made by including mixed traffic European flagship projects with speeds up to 250 km/h that are currently under construction. The latter are considered as it is highly unlikely that additional funds would be allocated for parallel HSR lines. Furthermore, HSR Sections that do not cover more than half the distance between two cites are excluded (e.g., Nuremberg-Munich, Zurich-Milan). Finally, the case study is complete, and the model can be applied. The obtained results presented in the next chapter.

4 Results

In the following Section the result of the application of the model to the cases study are discussed. Firstly, the results are reported (Section 4.1), then the model dynamics are discussed (Section 4.2), followed by a result analysis considering both the implications of a centralized decision making process (Section 4.3) and the detailed infrastructural representation (Section 4.4).

4.1 Network Evolution

The first Section presents the sequential iterative evolution in Figure 8. Dark blue represents the existing HSR Base Network (Section 3.5), orange depicts lines under construction while light blue highlights new lines entering in operation. The obtained network evolution, based on historical budget trends, adds 13,000 km of new HSR lines, more than doubling the base network. Significant HSR network expansions are witnessed in central, eastern, and peripheral areas of Europe. Countries such as Germany, Poland, Czech Republic, Switzerland, the United Kingdom, and Austria experience extensive growth. Densification occurs in Switzerland, Germany, Belgium, Poland, and northern Italy. Peripheral connections like Athens-Bucharest, Stockholm-Bergen, Stockholm-Gothenburg, and Lisbon-Porto emerge. At the same time, Spain, Denmark, Estonia, Latvia and Lithuania do not whines any network expansion.

In the obtained scenario rail's mode share increases from 13% in 2023 to 27% in 2065, becoming more competitive with air over longer distances. The breakeven point where air and rail are equally competitive thus shift from 380 to 640 km. To achieve such growth, the model forecasts a total of 269 billion euros of present investments, to be spend progressively between 2023-2050 for achieving a NPV of 563 billion euros. The final Benefit-Cost ratio of such invest is 3.

The model's network configuration aligns with current TEN-T expansion plans but reveals differences mainly on cross-border Sections. This suggests that the model may underestimate demand flows and wider economic benefits, as well as potential alternative line designs for mixed traffic for example.

Compared to Grolle's (2020) work, differences in network configurations arise, particularly the Bordeaux-Bilbao, Amsterdam-Utrecht-Hamburg, and Berlin-Warsaw Sections. These variations highlight the potential impact of including a service layer with capacity constraints and frequencies within the network evolution.

In terms of network evolution, Ernst & Young (2023), estimate 35,000 km of network expansion, while Deutsche Bahn et al. (2023) estimates 21,000 km by 2050. Although these studies have assumed fixed network configuration goals, these differences suggest that historical budget trends may not achieve EU goals, highlighting the need for improved economical effort or better benefit estimation in investment appraisal.

In terms of costs and benefits, Erns & Young (2023) presents slightly different infrastructural cost values, ranging from 400 billion to 835 billion euros, and NPVs from 560 billion to 830 billion euros. Despite network size variations, EY's BCR between 2 and 4 aligns with the one of this work. This suggests that the higher costs factors of this work and reliance on travel time benefits might suggest potential overestimation of VOT or PLI indices.

In comparing mode share results, this study differs significantly from Deutsche Bahn (2023) and EY (2023), primarily due to network size and varied mode choice modelling. The dominance of private vehicles and the prevalence of air travel in this scenario suggest a need to refine and expand choice modelling parameters.

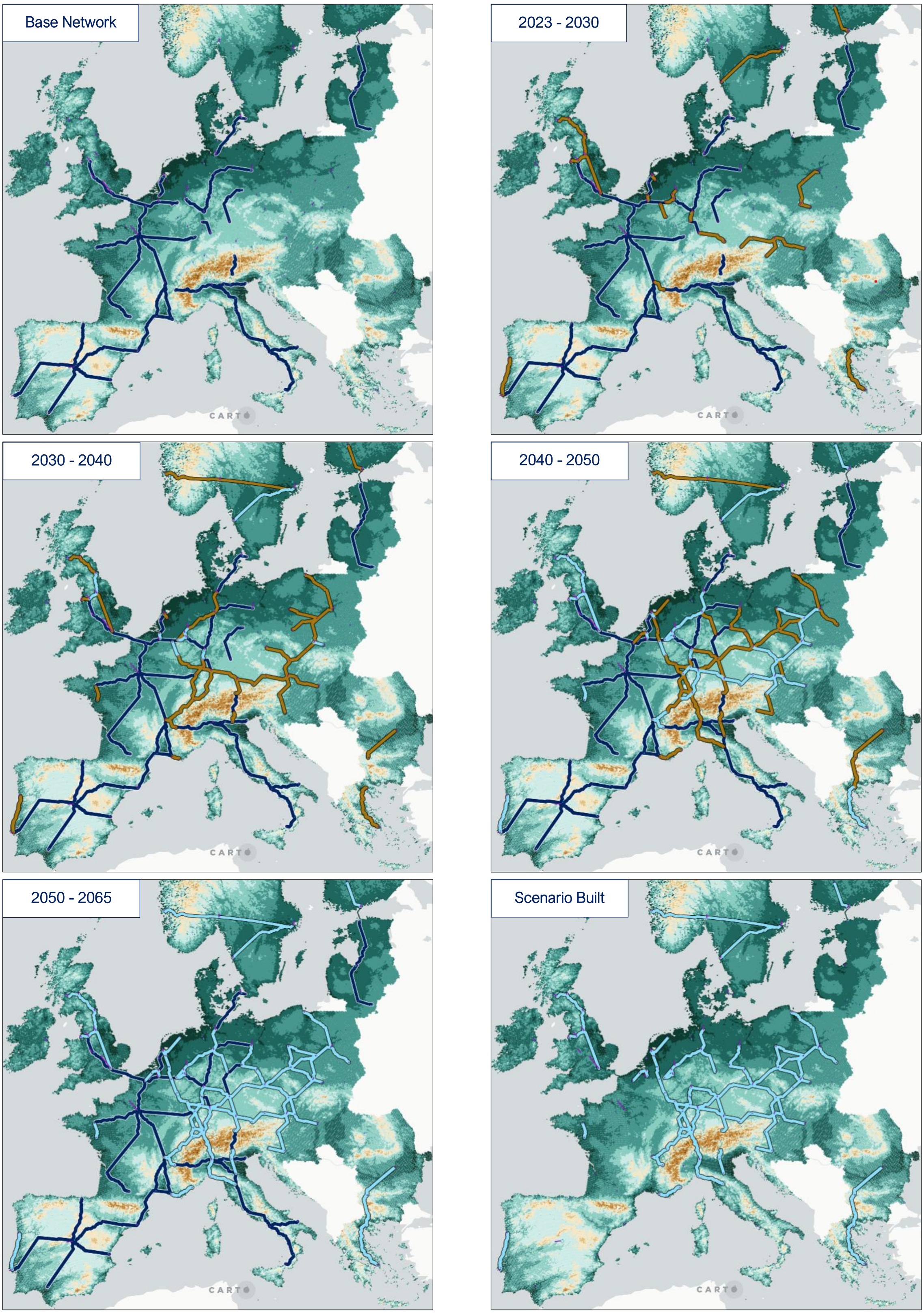


Figure 8 - Network evolution timeline. Existing lines in red, lines under construction in green, and completed lines in orange

4.2 Model Dynamics

The model highlights iterative dynamics that can be distinguished between how the evolution is shaped (Section 4.2.1) and types of investments that characterise this evolution (Section 4.2.2)

4.2.1 Preferential attachment and Path Dependency

The general sequential investment evolution emphasizes the dynamic interplay between passenger demand, travel time improvements, and infrastructural costs. The evolution process can be categorized into three phases: initial connections between major urban centres and from existing network Sections, expansion over longer distances between networks, and densification of areas with remaining potential improvements. This aligns with the principles of preferential attachment (Barabasi et al., 1999), where the 'richer get richer' phenomena is strictly related to population density and existing network structures. Nevertheless, some initial investments suggest the opposite, as they are not linked to any existing network. This demonstrates how the interplay between value of time, distance and population density plays as significant role in the evolution mechanism. Examples are the Stockholm to Gothenburg, Athens to Thessaloniki, or Budapest-Bratislava-Vienna connections.

While the model exhibits characteristics of preferential attachment, it also incorporates path dependency dynamics, as emphasized in Cats et al. (2021) reference study.

This means that candidates' BCRs are strictly related to the investment decisions taken in previous iterations, especially as consequence of previous travel times improvements which allow for more demand to benefit from the current investment. This is the case for example of consecutive investments such as the Warsaw-Lodz and Lodz-Katowice, or the Milan-Genova and Genova-Florence.

The impact of both dynamics is further highlighted by a modelling experiment assuming no infrastructure and exiting infrastructure. In Figure 8, it possible to visualize different network configurations for Germany for the former (left) or latter (right) case. Significantly different network evolution patterns are obtained, especially when connecting Berlin and Munich. When no infrastructure is considered, the model maximises the return on investment and therefore builds the connection via Dresden and Prague, where higher passenger volumes are attracted. But when existing infrastructure is considered, the model expands along the current Leipzig-Erfurt-Nuremberg Section because significant traffic volumes can be attracted at a lower cost.

Finally, the observed benefits distribution and iterative mechanism align with previous research respectively by Pablo-Marti et al. (2017) and Cats et al. (2021), leading to similar conclusions.

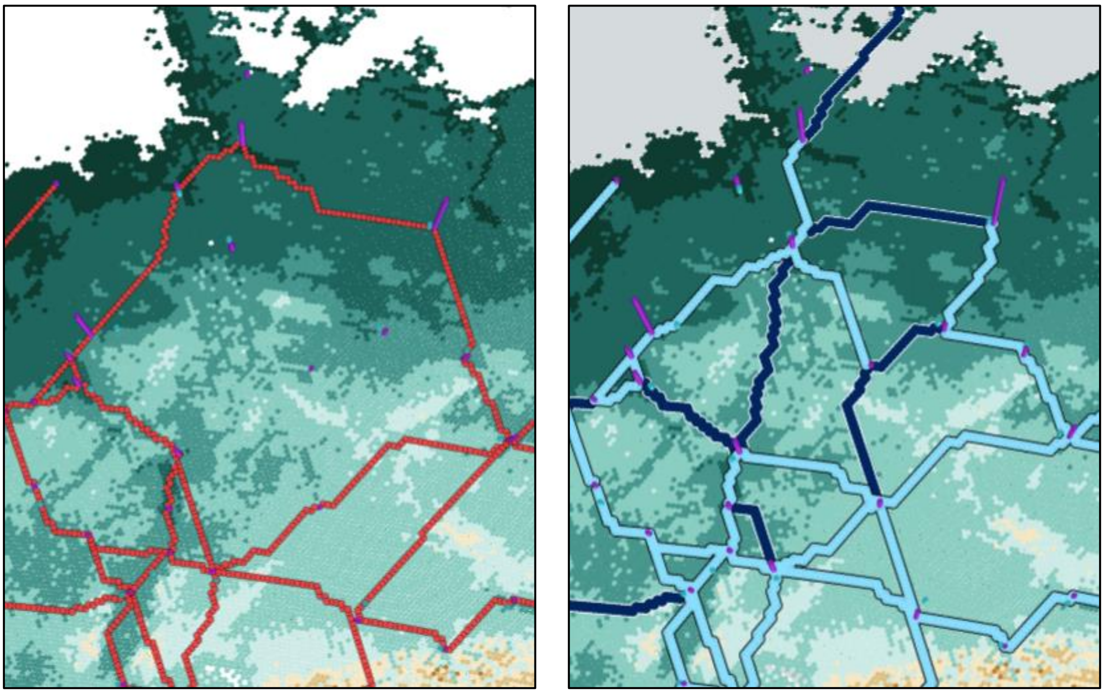


Figure 9 – Network evolution for Germany based on an empty (left) or initialized base network (right)

4.2.2 *Line Design in relation to Benefit Estimation*

Interestingly, the iterative expansion of the network reveals three distinct types of investments based on their characteristics and function within the network. Type one investments, such as the connections Mannheim-Frankfurt and Brussels-Antwerpen, bridge previously unconnected networks, eliminating gaps and enhancing benefits due to a large passenger increase. Type two investments, such as Leeds-London and Milan-Genova-Florence, create shortcuts parallel to existing infrastructure, improving both passenger volumes and travel times. Lastly, type three investments like Oslo-Bergen and Bucharest-Sofia, connect distant centres in peripheral areas, enhancing benefits due to substantial travel time improvements but moving lower passenger volumes due to their peripheral locations.

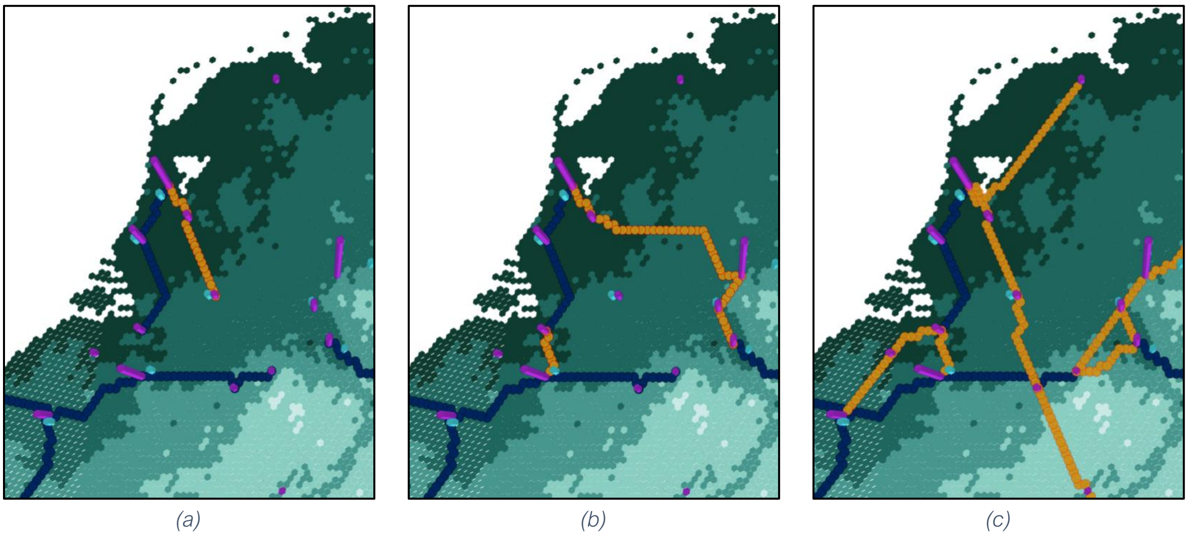
The model does not show a precise behaviour in the choice of these links, solely demonstrating the intricate interplay between demand, travel time, and infrastructure costs in network evolution. These considerations can become valuable when analysing the functional design of each investment considering detailed infrastructural planning processes.

4.3 Implications of a Centralized Decision-Making Process

The model assumes a centrally managed investment process with dedicated budget. The consequences of this assumptions are analysed in terms of network design (4.3.1), budget allocations (4.3.2) and appraisal (4.3.3)

4.3.1 Network Design

To emphasize how network design is affected by different decision-making process, the case of the Netherlands is used. Figure 9 illustrates the varying decisions made by the model under national (a), cross-border (b), and European (c) perspectives. It highlights that a broader view in infrastructure planning can lead to more efficient resource allocation and optimal investment decisions. This is because the model has the ability to forecast the impact of infrastructural investment over longer distance and evaluate potential benefits also outside and beyond neighbouring countries. The findings suggest that existing European infrastructure, developed primarily through national perspectives, may not be the most efficient network configuration from a broader European viewpoint.


(a)

(b)

(c)

Figure 9 - Network evolution under national (a), cross-border (b) and European (c) perspective

4.3.2 Budget Allocations

The concept of a centrally managed budget for common challenges resembles the EU budget's mechanism, where countries contribute to common funds based on their income, and the EU reallocates the capital according to its priorities (European Parliament, 2023). In the model, as in the reality (European Union Budget, 2023), this leads to some countries contributing more than they gain from the investment plan. For some of the ones contributing more there is still a return on investment, but for the remaining majority, contributing more generates negative BCRs. This suggests that a centralized decision making process should take into account compensative measures to address misalignment between countries.

4.3.3 Appraisal Process

The main implications of a common appraisal process can be recognised within the benefit estimation. Analysing country specific gains reveals that countries without HSR investments on their territory can still benefit from neighbouring countries' investments in terms of travel time and externality savings. This highlights the importance of including spill-over effects within a broader appraisal framework beyond national borders. Additionally, including other attributes such as wider economic benefits and induced demand, suggests that these spill-over effects could be further enhanced. Secondly, by analysing the mode share evolution and the change rate of rail's share between iterations, it is

4.4 Detailed Infrastructure Modelling

Finally, the results obtained allow to formulate some considerations on the detailed hexagonal infrastructural modelling technique adopted in this work. With a cost underestimation of 13% and a distance overestimation of 12% as compared to existing infrastructure, the model does not perform badly. The detail level chosen can be therefore considered as a starting point for a methodology that shows great improvement and detailed representation potentials. Not only for infrastructural and topographical analyses, but hexagonal indexing could also be used to granularly model the demand distribution on aggregated level. In conclusion, it is recommended that this approach is further studied and improved in terms or resolution level, in order to achieve an even more realistic representation of both topographical and demand specific feature.

5 Conclusions

Overall, this work has provided a modelling methodology to address the creation of a long-term sequential investment plan to achieve a unified European HSR network. The methodology relies on the assumption of coordinating appraisal and investment procedures form a centralized perspective, in order to maximise appraisal effectiveness and investment efficiency. Furthermore, special focus has been given to the infrastructure modelling, for a more precise estimation of the impacts of topography and spatial features on the final cost specifications.

Findings related to the practical application of the model to the context of a Trans-European HSR network based on current budget trends, reveals substantial expansion. Over 13,000 km of new HSR lines are added, effectively doubling the existing base network. Notable growth occurs in central, eastern, and peripheral European regions, with countries like Germany, Poland, the United Kingdom, and others experiencing significant development. Densification is observed in Switzerland, Germany, Belgium, Poland, and northern Italy. Peripheral connections, such as Athens-Bucharest and Stockholm-Bergen, emerge. Rail's mode share is projected to rise from 13% in 2023 to 27% in 2065, notably challenging air travel for longer distances up to 1500km. Achieving this expansion entails 269 billion euros of investments over the period 2023-2050, with 834 billion euros benefits divided between 604 billion travel time savings and 230 billion euros in externality savings. The final Benefit-Cost ratio obtained is 3.

The modelling outcomes reveal a dynamic interplay between passenger demand, travel time improvements, and infrastructural costs, unfolding in three phases of network evolution: Expansion from utility centres, network extension over longer distances, densification. The model is thus aligned with preferential attachment principles, emphasizing the 'rich get richer' phenomenon tied to population density and existing network structures. However, intriguingly, some initial investments deviate from this pattern, suggesting that the interplay of value of time, distance, and population density has a significant influence. Notably, the model demonstrates path dependency dynamics, where investment decisions depend on previous iterations, driven by past travel time improvements. Overall, these findings align with prior research, further demonstrating the functioning based on scale free dynamics and preferential attachment.

Concerning infrastructure modelling, the results underscore the potential of the hexagonal indexing technique employed in this study. While it exhibits a 13% underestimation in costs and a 12% overestimation in distances compared to existing infrastructure due to low level of detail, it can be concluded that methodology is a promising methodology to discretize topographical features. Together with the newly introduced three dimensional layering system, it is advisable to further investigate and refine this approach, particularly in terms of resolution level. This would enable a more accurate representation of topographical and demand-specific features.

The conclusions pertaining the policy implications of this work highlight how adopting a centralized appraisal and investment process could notably broaden the appraisal context and increase the efficiency of budget allocations from a European perspective. Enhanced modelling techniques and parameters could better harness cross-border spill-over effects and map utility pattern over longer distances and across borders. Economically, such an approach impacts budget contributions, investment allocations, and benefits distribution among the countries involved. It is thus concluded that a centralized appraisal and investment process does benefit the overall sequential investment procedures, but such plans should be carefully drafted by including compensation measures to convince all countries of the benefits in joining.

The iterative network growth model presented here offers valuable insights, but several assumptions could be relaxed for improved accuracy. Recommendations for future research include refining terrain modelling by increasing detail and incorporating land use, enhancing utility formulation with parameters like travel costs and comfort, and modelling service provision and infrastructural capacity for more realistic network design. The appraisal process could benefit from including a wider range of factors impacted by HSR investments, such as land use, labour markets, GDP, and innovation. Special attention should be given to corridor construction, optimizing link creation and exploring alternative route models. These adjustments would enhance the model's applicability and results, offering a more comprehensive and detailed perspective on European HSR network growth. With limited literature on iterative evolution in the European HSR context, this study introduces a pioneering methodology as a continuation of the works of on Donners (2016), Grolle (2019), and Cats et al. (2021). To this end, it is recommended that future research endeavours consider applying the developed model to analyse the dynamic interaction between service design and infrastructure expansion in the context of high-speed rail networks. This holistic approach would provide a comprehensive understanding of how service improvements and infrastructural developments influence each other over time, offering valuable insights for efficient planning and optimization

References

Barabasi, A., & Albert, R. (1999). Emergence of scaling in random networks. Science, 286 (5439), pp. 509 - 512, Cited 26753 times. DOI: 10.1126/science.286.5439.509

Barrón, I., Campos, J., Gagnepain, P., Nash, C., Ulied, A., Vickerman, R., & de Rus, G. (2009). Economic Analysis of High Speed Rail in Europe.

Black, W. (1971). An iterative model for generating transportation networks.

Campos, J., de Rus, G., & Barron, I. (2007). The cost of building and operating a new high speed rail line. University Library of Munich, Germany, MPRA Paper.

Chorus, C. G. (2010). A New Model of Random Regret Minimization. European Journal of Transport and Infrastructure Research, 10(2). https://doi.org/10.18757/ejtir.2010.10.2.2881

Creel, J., Holzner, M., Saraceno, F., Watt, A., & Wittwer, J. (2020). How to spend it: A proposal for a European Covid-19 recovery programme. The Vienna Institute for International Economic Studies (wiiw).

Deutsche Bahn, & PTV group. (2023). Metropolitan network: a strong European railway for an ever closer union.

Ernst & Young (EY). (2023). Smart and affordable rail services in the EU: a socio-economic and environmental study for High-Speed in 2030 and 2050.

European Commission. (2013). Mobility and Transport. Trans-European Transport Network (TEN-T). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013R1315

European Commission. (2014). Guide to Cost-Benefit Analysis of Investment Projects. Economic appraisal tool for cohesion policy 2014-2020. https://wayback.archive-it.org/12090/20221203224508/https:/ec.europa.eu/inea/sites/default/files/cba_guide_cohesion_policy.pdf

European Commission. (2020a). Sustainable and Smart Mobility strategy. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789

European Commission. (2020b). Long-distance cross-border passenger rail services. Study contract MOVE/2020/OP/0013 European Commission commissioned to Steer and KWC. https://op.europa.eu/en/publication-detail/-/publication/34244751-6ea3-11ec-9136-01aa75ed71a1

González-González, E., Marsden, G., & Smith, A. (2010). How important are environmental factors in the case for High-Speed Rail? A comparison of the United Kingdom and Spain.

Holzner, M., Heimberge, P., & Kochnev, A. (2018). A 'European Silk Road'. Research Report 430. The Vienna Institute for International Economic Studies (wii).

Holzner, M., Weber, K., Zahid, M.U., & Zangl, M. (2022). Environmental Impact Evaluation of a European High Speed Railway Network along the 'European Silk Road'. The Vienna Institute for International Economic Studies (wii).

Kortazar, A., Bueno, G., & Hoyos, D. (2021). Dataset for the life cycle assessment of the high speed rail network in Spain. https://doi.org/10.1016/j.dib.2021.107006.

Levinson, D., & Yerra, B. (2005). The emergence of hierarchy in transportation networks.

Nash, A. (2007). Europe's High-Speed Rail Network: Maturation and Opportunities.

Oded, C., & Birch, N. (2021). Multi-modal network evolution in polycentric regions. Journal of Transport Geography, 96:103159-. doi: 10.1016/J.JTRANGEO.2021.103159

Oded, C., Vermeulen, A., Warnier, M., & van Lint, H. (2020). Modelling growth principles of metropolitan public transport networks. Journal of Transport Geography, 82:102567. doi: 10.1016/J.JTRANGEO.2019.102567

Pablo-Martí, F., & Sánchez, A. (2017). Improving transportation networks: Effects of population structure and decision making policies. Scientific Reports. 7. 10.1038/s41598-017-04892-2

Peters, J. Han, E., Kumar, A. Peeta, S. & DeLaurentis, A. (2014). Incorporating High Speed Passenger Rail into a Multimodal Network Model for Improved Regional Transportation Planning.

UIC. (2015). High-Speed Rail Fast track to Sustainable Mobility. https://uic.org/IMG/pdf/high_speed_brochure.pdf

UIC. (2018). High-speed rail around the world. Historical, geographical and technological development

UNECE. (2021). Trans-European Railway High-Speed. Master plan study. A general background to support further required studies. Phase 2

UNECE. (2021). Trans-European Railway High-Speed. Master plan study. Phase 1

Vickerman, R. (1997) High-speed rail in Europe: experience and issues for future development. Ann Reg Sci 31, 21–38. https://doi.org/10.1007/s001680050037.

Xie, F., & Levinson, D. (2007a). Modelling the Growth of Transportation Networks: A comprehensive review. Research Papers in Economics.

APPENDIX B – Urban Hubs

City	Elevation	Population	GDPpc	Country	Language 1	Language 2	Schengen	Federation	Ratio_Population	Ratio_GDPpc	Ratio_Urbanized	Airports	Area	City_Weight
Linz	261	651950	50562	Austria	German		Yes	Yes	0.404	1.164	0.877	1	875	0.732
Vienna	213	2983513	49808	Austria	German		Yes	Yes	1.848	1.146	0.877	1	3104	1.554
Salzburg	425	375489	59560	Austria	German		Yes	Yes	0.233	1.371	0.877	1	368	0.603
Graz	425	657316	47905	Austria	German		Yes	Yes	0.407	1.102	0.877	1	978	0.715
Innsbruck	958	352507	49916	Austria	German		Yes	Yes	0.218	1.149	0.877	1	352	0.535
Antwerp	11	1139663	51438	Belgium	Dutch		Yes	Yes	0.706	1.184	2.814	0	2393	0.545
Brussels	32	3284548	55819	Belgium	French	Dutch	Yes	Yes	2.034	1.285	2.814	1	1851	0.964
Gent	1	645813	47612	Belgium	Dutch		Yes	Yes	0.400	1.096	2.814	0	1814	0.395
Liege	137	793118	31801	Belgium	French		Yes	Yes	0.491	0.732	2.814	0	2710	0.357
Plovdiv	161	536672	16083	Bulgaria	Bulgarian		No	No	0.332	0.370	0.277	0	262	0.666
Sofia	536	1553106	38906	Bulgaria	Bulgarian		No	No	0.962	0.895	0.277	1	1352	1.762
Zagreb	250	1217131	34531	Croatia	Croatian		No	No	0.754	0.795	0.315	1	1571	1.379
Brno	271	731860	32740	Czech Republic	Czech		Yes	No	0.453	0.753	0.683	0	1560	0.707
Ostrava	210	711860	26887	Czech Republic	Czech		Yes	No	0.441	0.619	0.683	0	1043	0.632
Prague	195	2231212	58048	Czech Republic	Czech		Yes	No	1.382	1.336	0.683	1	2897	1.644
Aarhus	24	521123	41760	Denmark	Danish		Yes	No	0.323	0.961	0.838	1	1711	0.608
Copenhagen	17	1933919	56748	Denmark	Danish	Swedish	Yes	No	1.198	1.306	0.838	1	3406	1.366
Tallinn	39	390860	44056	Estonia	Estonian		Yes	No	0.242	1.014	0.127	1	720	1.392
Helsinki	6	1507140	53141	Finland	Finnish		Yes	No	0.933	1.223	0.084	1	3066	3.675
Tampere	94	444370	37469	Finland	Finnish		Yes	No	0.275	0.862	0.084	1	1044	1.676
Bordeaux	2	1277949	37992	France	French		Yes	No	0.791	0.874	0.619	1	2165	1.057
Grenoble	746	670721	35755	France	French		Yes	No	0.415	0.823	0.619	0	1279	0.743
Lille	27	1518544	32923	France	French		Yes	No	0.940	0.758	0.619	1	966	1.073
Lyon	280	2113104	48478	France	French		Yes	No	1.309	1.116	0.619	1	3516	1.536
Marseille	17	1284351	38455	France	French		Yes	No	0.795	0.885	0.619	1	1599	1.066
Montpellier	23	729272	31918	France	French		Yes	No	0.452	0.734	0.619	1	1303	0.732
Nantes	18	989758	38760	France	French		Yes	No	0.613	0.892	0.619	1	2682	0.940
Nice	22	1018815	39059	France	French		Yes	No	0.631	0.899	0.619	1	2109	0.957
Paris	71	12924097	62665	France	French		Yes	No	8.004	1.442	0.619	1	6778	4.318
Rennes	45	697990	37976	France	French		Yes	No	0.432	0.874	0.619	1	1613	0.781
Rouen	13	699493	33560	France	French		Yes	No	0.433	0.772	0.619	0	1876	0.735
Strasbourg	144	824733	37209	France	French	German	Yes	No	0.511	0.856	0.619	1	1355	0.841
Toulon	258	570893	26654	France	French		Yes	No	0.354	0.613	0.619	1	1265	0.592
Toulouse	193	1423458	43506	France	French		Yes	No	0.882	1.001	0.619	1	3321	1.194
Aachen	183	554910	42462	Germany	German		Yes	Yes	0.344	0.977	1.497	0	121.68	0.474
Berlin	32	5303922	41572	Germany	German		Yes	Yes	3.285	0.957	1.497	1	3572	1.449
Bremen	4	1274968	42408	Germany	German		Yes	Yes	0.790	0.976	1.497	1	1287	0.718
Dusseldorf	46	1554077	63623	Germany	German		Yes	Yes	0.962	1.464	1.497	1	661	0.970
Frankfurt am Main	102	2710501	61956	Germany	German		Yes	Yes	1.679	1.426	1.497	1	3323	1.265
Hamburg	17	3315036	54531	Germany	German		Yes	Yes	2.053	1.255	1.497	1	3206	1.312
Hannover	54	1316467	48966	Germany	German		Yes	Yes	0.815	1.127	1.497	1	1883	0.783
Karlsruhe	117	756983	54230	Germany	German		Yes	Yes	0.469	1.248	1.497	1	1298	0.625
Kiel	32	647622	38655	Germany	German		Yes	Yes	0.401	0.890	1.497	0	714	0.488

Cologne	53	2002550	53863	Germany	German		Yes	Yes	1.240	1.240	1.497	1	3263	1.013
Leipzig	113	1043613	36704	Germany	German		Yes	Yes	0.646	0.845	1.497	1	1140	0.604
Mannheim	95	1187725	49981	Germany	German		Yes	Yes	0.736	1.150	1.497	0	2160	0.752
Munich	513	2907752	74989	Germany	German		Yes	Yes	1.801	1.726	1.497	1	2638	1.441
Ruhr	67	5115088	36453	Germany	German		Yes	Yes	3.168	0.839	1.497	1	6303	1.333
Saarbrucken	370	800222	40370	Germany	German		Yes	Yes	0.496	0.929	1.497	0	830	0.555
Stuttgart	270	2787449	60413	Germany	German		Yes	Yes	1.726	1.390	1.497	1	2159	1.266
Dresden	138	1343213	35516	Germany	German		Yes	Yes	0.832	0.817	1.497	1	1587	0.674
Nuremberg	310	1348820	53943	Germany	German		Yes	Yes	0.835	1.241	1.497	0	1874	0.832
Erfurt	189	527548	36366	Germany	German		Yes	Yes	0.327	0.837	1.497	0	547	0.427
Athens	50	3530371	34456	Greece	Greece		Yes	No	2.186	0.793	0.508	1	2246	1.847
Thessaloniki	51	1050568	21381	Greece	Greece		Yes	No	0.651	0.492	0.508	1	1107	0.794
Budapest	119	2997506	43878	Hungary	Hungarian		Yes	No	1.856	1.010	0.472	1	4197	1.992
Dublin	32	1971242	90634	Ireland	Irish		No	No	1.221	2.086	0.414	1	2245	2.480
Bari	0	729385	25951	Italy	Italian		Yes	No	0.452	0.597	1.135	1	487	0.488
Bologna	49	1019539	48675	Italy	Italian		Yes	No	0.487	1.120	1.135	1	900	0.693
Brescia	122	477619	40216	Italy	Italian		Yes	No	0.296	0.925	1.135	1	560	0.491
Catania	0	635614	22144	Italy	Italian		Yes	No	0.394	0.510	1.135	1	482	0.420
Florence	77	794659	49373	Italy	Italian		Yes	No	0.492	1.136	1.135	1	1205	0.702
Genoa	49	692806	42542	Italy	Italian		Yes	No	0.429	0.979	1.135	1	860	0.608
Milan	124	4965808	54598	Italy	Italian		Yes	No	3.075	1.256	1.135	1	3393	1.845
Naples	183	3362207	23178	Italy	Italian		Yes	No	2.082	0.533	1.135	1	2318	0.989
Palermo	35	1001778	21999	Italy	Italian		Yes	No	0.620	0.506	1.135	1	675	0.526
Rome	59	4335555	44734	Italy	Italian		Yes	No	2.685	1.029	1.135	1	2696	1.561
Turin	242	1733674	38850	Italy	Italian		Yes	No	1.074	0.894	1.135	1	1708	0.920
Venice	-2	557748	35439	Italy	Italian		Yes	No	0.345	0.816	1.135	1	60	0.498
Verona	95	515613	39772	Italy	Italian		Yes	No	0.319	0.915	1.135	1	620	0.508
Padua	13	534896	40202	Italy	Italian		Yes	No	0.331	0.925	1.135	0	904	0.520
Mediopadana	40	678542	43632	Italy	Italian		Yes	No	0.420	1.004	1.135	0	752	0.610
Stretto	0	1116013	18315	Italy	Italian		Yes	No	0.691	0.421	1.135	1	452	0.507
Trento	961	239900	34245	Italy	Italian		Yes	No	0.149	0.788	1.135	0	332	0.321
Trieste	122	232405	30365	Italy	Italian		Yes	No	0.144	0.699	1.135	1	172	0.298
Riga	3	930245	35310	Latvia	Latvian		Yes	No	0.576	0.813	0.211	1	1593	1.489
Vilnius	114	528471	45571	Lithuania	Lithuanian		Yes	No	0.327	1.049	0.183	1	850	1.368
Kaunas	80	288575	31705	Lithuania	Lithuanian		Yes	No	0.179	0.730	0.183	1	952	0.843
Luxembourg	287	610825	100155	Luxembourg	German	French	Yes	No	0.378	2.305	3.461	1	1055	0.502
Amsterdam	0	2862590	65254	Netherlands	Dutch		Yes	No	1.773	1.502	2.420	1	1294	1.049
Eindhoven	18	760059	55962	Netherlands	Dutch		Yes	No	0.471	1.288	2.420	1	1381	0.500
Groningen	7	478761	46076	Netherlands	Dutch		Yes	No	0.296	1.060	2.420	0	995	0.360
Rotterdam	-4	1860582	48924	Netherlands	Dutch		Yes	No	1.152	1.126	2.420	1	2943	0.732
Utrecht	1	898712	59893	Netherlands	Dutch		Yes	No	0.557	1.378	2.420	0	1039	0.563
Bergen	0	419854	45633	Norway	Norwegian		Yes	No	0.260	1.050	0.069	1	846	1.987
Oslo	40	1398715	59952	Norway	Norwegian		Yes	No	0.866	1.380	0.069	1	4272	4.156
Gdansk	-1	1161208	35053	Poland	Polish		Yes	No	0.719	0.807	0.592	1	1475	0.990
Katowice	293	2496193	31352	Poland	Polish		Yes	No	1.546	0.721	0.592	1	5198	1.373
Krakow	205	1410424	36368	Poland	Polish		Yes	No	0.873	0.837	0.592	1	2630	1.111
Lodz	195	907836	33597	Poland	Polish		Yes	No	0.562	0.773	0.592	0	1996	0.857

Lublin	192	670334	25661	Poland	Polish		Yes	No	0.415	0.591	0.592	0	1434	0.644
Poznan	84	988374	46360	Poland	Polish		Yes	No	0.612	1.067	0.592	0	2523	1.050
Rzeszow	200	505486	24861	Poland	Polish		Yes	No	0.313	0.572	0.592	1	1078	0.550
Warsaw	121	3181548	60725	Poland	Polish		Yes	No	1.970	1.397	0.592	1	4181	2.157
Wroclaw	122	877966	44072	Poland	Polish		Yes	No	0.544	1.014	0.592	1	2206	0.965
Lisbon	0	3008000	37834	Portugal	Portuguese		Yes	No	1.863	0.871	0.681	1	1575	1.543
Porto	87	1280190	27989	Portugal	Portuguese		Yes	No	0.793	0.644	0.681	1	1487	0.866
Bucharest	86	2212830	57196	Romania	Romanian		No	No	1.370	1.316	0.205	1	2091	2.963
Cluj-Napoca	365	383849	33213	Romania	Romanian	Hungarian	No	No	0.238	0.764	0.205	1	836	0.940
Iasi	128	393605	19043	Romania	Romanian		No	No	0.244	0.438	0.205	1	455	0.721
Timisoara	91	351851	30998	Romania	Romanian		No	No	0.218	0.713	0.205	1	657	0.870
Bratislava	136	440611	69177	Slovakia	Slovakian		Yes	No	0.273	1.592	0.242	1	833	1.341
Kosice	199	367712	10497	Slovakia	Slovakian		Yes	No	0.228	0.242	0.242	1	555	0.477
Ljubljana	312	292988	46196	Slovenia	Slovenian		Yes	No	0.181	1.063	0.212	1	654	0.954
Barcelona	2	5034925	40204	Spain	Spanish		Yes	No	3.118	0.925	0.492	1	1967	2.421
Bilbao	253	1007915	41131	Spain	Spanish		Yes	No	0.624	0.947	0.492	1	1003	1.096
Madrid	669	6882461	45566	Spain	Spanish		Yes	No	4.262	1.049	0.492	1	4270	3.014
Seville	14	1549641	26797	Spain	Spanish		Yes	No	0.960	0.617	0.492	1	931	1.097
Valencia	15	1748142	29981	Spain	Spanish		Yes	No	1.083	0.690	0.492	1	2093	1.232
Zaragoza	198	768643	37188	Spain	Spanish		Yes	No	0.476	0.856	0.492	0	693	0.910
Gothenburg	62	1037675	44287	Sweden	Swedish		Yes	No	0.643	1.019	0.136	1	2653	2.197
Stockholm	14	2344124	63365	Sweden	Swedish		Yes	No	1.452	1.458	0.136	1	2536	3.949
Malmo	16	680335	39642	Sweden	Swedish		Yes	No	0.421	0.912	0.136	1	716	1.683
Basel	264	550152	84689	Switzerland	French	German	Yes	Yes	0.341	1.949	1.048	1	554	0.796
Geneva	406	597269	74794	Switzerland	French		Yes	Yes	0.370	1.721	1.048	1	350	0.779
Zurich	428	1384728	71833	Switzerland	German		Yes	Yes	0.858	1.653	1.048	1	2588	1.163
Bern	498	419983	57060	Switzerland	German		Yes	Yes	0.260	1.313	1.048	0	837	0.571
Birmingham	111	3116866	32091	United Kingdom	English		No	No	1.930	0.738	1.625	1	1786	0.936
Edinburgh	56	907580	48229	United Kingdom	English		No	No	0.562	1.110	1.625	1	1448	0.620
Glasgow	4	1845020	35426	United Kingdom	English		No	No	1.143	0.815	1.625	1	2350	0.757
Liverpool	31	1544216	30141	United Kingdom	English		No	No	0.956	0.694	1.625	1	1038	0.639
London	9	12396541	62395	United Kingdom	English		No	No	7.677	1.436	1.625	1	6605	2.604
Manchester	26	3383986	37244	United Kingdom	English		No	No	2.096	0.857	1.625	1	2182	1.051
Newcastle upon Tyne	14	1186198	29965	United Kingdom	English		No	No	0.735	0.690	1.625	1	2249	0.558
Leeds	33	2641062	33929	United Kingdom	English		No	No	1.636	0.781	1.625	1	3044	0.886

APPENDIX C – Infrastructural Costs

COUNTRY SPECIFIC COST PER KM		
Country	Surface (ml/pkm)	Underground (ml/pkm)
Austria	23	65
Belgium	26	74
Bulgaria	15	43
Croatia	12	36
Czech Republic	19	54
Denmark	15	44
Estonia	6	16
Finland	10	29
France	35	100
Germany	45	129
Greece	18	51
Hungary	12	34
Ireland	12	36
Italy	36	106
Latvia	5	15
Lithuania	6	16
Luxembourg	21	60
Netherlands	34	98
Norway	20	58
Poland	12	36
Portugal	17	50
Romania	15	42
Slovakia	19	56
Slovenia	17	48
Spain	27	77
Sweden	17	48
Switzerland	29	84
United Kingdom	43	125

SEA PROJECTS SPECIFIC COST PER KM							
Project	Country	Infrastructure Cost	Length (km)	Real Length (km)	Nr. Edges	Cost pkm (ml/eur)	Real Cost pkm (ml/eur)
Stretto di Messina Bridge	Italy	10bn	3.5	14	2	2857	714
Channel Tunnel	France	16.47bn	50.46	56	8	326	294
Oresund Bridge	Denmark	5.46bn	16	28	4	341	195
Fehmarn Tunnel	Denmark	6.41bn	19	35	5	337	183
New Little Belt Bridge	Denmark	1.98bn	1.7	14	2	1163	141
Great Belt Bridge	Denmark	5.06bn	6.79	35	5	745	145
Storstrom strait	Denmark	3.95bn	3.2	14	2	1236	282
Gulf of Finland	Finland	15bn	100	105	15	150	143

APPENDIX D – HSR Links

City1	City2	Elevation1	Country1	Elevation2	Country2	Distance	Investment	Cost km	Travel Time
Vienna	Linz	213	Austria	261	Austria	159	3450000000	22	0.90
Salzburg	Linz	425	Austria	261	Austria	116	2484000000	21	0.66
Salzburg	Vienna	425	Austria	213	Austria	269	5935000000	22	1.53
Graz	Linz	425	Austria	261	Austria	190	4140000000	22	1.08
Graz	Vienna	425	Austria	213	Austria	159	3384000000	21	0.90
Innsbruck	Salzburg	958	Austria	425	Austria	159	3982000000	25	0.90
Brussels	Antwerp	32	Belgium	11	Belgium	55	1259000000	23	0.31
Gent	Antwerp	1	Belgium	11	Belgium	61	1417000000	23	0.35
Gent	Brussels	1	Belgium	32	Belgium	67	1574000000	23	0.38
Liege	Antwerp	137	Belgium	11	Belgium	135	3305000000	25	0.76
Liege	Brussels	137	Belgium	32	Belgium	104	2518000000	24	0.59
Sofia	Plovdiv	536	Bulgaria	161	Bulgaria	135	1888000000	14	0.76
Zagreb	Vienna	250	Croatia	213	Austria	306	4200000000	14	1.73
Zagreb	Graz	250	Croatia	425	Austria	147	2416000000	16	0.83
Brno	Vienna	271	Czech Republic	213	Austria	135	2619000000	19	0.76
Ostrava	Vienna	210	Czech Republic	213	Austria	245	4674000000	19	1.39
Ostrava	Brno	210	Czech Republic	271	Czech Republic	147	2615000000	18	0.83
Prague	Linz	195	Czech Republic	261	Austria	226	4227000000	19	1.28
Prague	Vienna	195	Czech Republic	213	Austria	287	5462000000	19	1.63
Prague	Salzburg	195	Czech Republic	425	Austria	312	6135000000	20	1.77
Prague	Brno	195	Czech Republic	271	Czech Republic	208	3753000000	18	1.18
Prague	Ostrava	195	Czech Republic	210	Czech Republic	312	4990000000	16	1.77
Copenhagen	Aarhus	17	Denmark	24	Denmark	318	7906000000	25	1.80
Helsinki	Tallinn	6	Finland	39	Estonia	110	11507000000	105	0.62
Tampere	Tallinn	94	Finland	39	Estonia	294	13328000000	45	1.66
Tampere	Helsinki	94	Finland	6	Finland	190	1821000000	10	1.08
Lille	Antwerp	27	France	11	Belgium	135	3439000000	26	0.76
Lille	Brussels	27	France	32	Belgium	116	2967000000	26	0.66
Lille	Gent	27	France	1	Belgium	80	2023000000	25	0.45
Lille	Liege	27	France	137	Belgium	202	5170000000	26	1.14
Lyon	Grenoble	280	France	746	France	116	3798000000	33	0.66
Marseille	Grenoble	17	France	746	France	239	8018000000	34	1.35
Marseille	Lyon	17	France	280	France	300	10127000000	34	1.70
Montpellier	Lyon	23	France	280	France	281	9495000000	34	1.60
Montpellier	Marseille	23	France	17	France	135	4431000000	33	0.76
Nice	Grenoble	22	France	746	France	275	9284000000	34	1.56
Nice	Lyon	22	France	280	France	361	12237000000	34	2.05
Nice	Marseille	22	France	17	France	177	5908000000	33	1.01
Paris	Antwerp	71	France	11	Belgium	342	10506000000	31	1.94
Paris	Brussels	71	France	32	Belgium	294	9246000000	31	1.66
Paris	Gent	71	France	1	Belgium	318	9876000000	31	1.80

Paris	Liege	71	France	137	Belgium	336	10187000000	30	1.91
Paris	Bordeaux	71	France	2	France	550	18778000000	34	3.12
Paris	Grenoble	71	France	746	France	544	18567000000	34	3.09
Paris	Lille	71	France	27	France	245	8229000000	34	1.39
Paris	Lyon	71	France	280	France	434	14769000000	34	2.46
Paris	Marseille	71	France	17	France	679	23209000000	34	3.85
Paris	Montpellier	71	France	23	France	630	21521000000	34	3.57
Paris	Nantes	71	France	18	France	398	13503000000	34	2.25
Rennes	Nantes	45	France	18	France	116	3798000000	33	0.66
Rennes	Paris	45	France	71	France	367	12448000000	34	2.08
Rouen	Lille	13	France	27	France	220	7385000000	34	1.25
Rouen	Paris	13	France	71	France	128	4220000000	33	0.73
Strasbourg	Paris	144	France	71	France	422	14347000000	34	2.39
Toulon	Marseille	258	France	17	France	61	1899000000	31	0.35
Toulon	Nice	258	France	22	France	135	4431000000	33	0.76
Toulouse	Bordeaux	193	France	2	France	239	8018000000	34	1.35
Toulouse	Montpellier	193	France	23	France	208	6963000000	33	1.18
Toulouse	Paris	193	France	71	France	654	22365000000	34	3.71
Aachen	Antwerp	183	Germany	11	Belgium	165	4265000000	26	0.94
Aachen	Brussels	183	Germany	32	Belgium	135	3478000000	26	0.76
Aachen	Liege	183	Germany	137	Belgium	49	1275000000	26	0.28
Aachen	Paris	183	Germany	71	France	379	11462000000	30	2.15
Berlin	Prague	32	Germany	195	Czech Republic	385	8040000000	21	2.18
Berlin	Copenhagen	32	Germany	17	Denmark	557	24816000000	45	3.16
Bremen	Paris	4	Germany	71	France	660	23287000000	35	3.75
Dusseldorf	Antwerp	46	Germany	11	Belgium	183	5679000000	31	1.04
Dusseldorf	Brussels	46	Germany	32	Belgium	202	6151000000	30	1.14
Dusseldorf	Liege	46	Germany	137	Belgium	116	4277000000	37	0.66
Dusseldorf	Paris	46	Germany	71	France	446	14135000000	32	2.53
Dusseldorf	Aachen	46	Germany	183	Germany	73	3002000000	41	0.42
Frankfurt am Main	Paris	102	Germany	71	France	544	18569000000	34	3.09
Frankfurt am Main	Strasbourg	102	Germany	144	France	208	8418000000	40	1.18
Frankfurt am Main	Aachen	102	Germany	183	Germany	232	9058000000	39	1.32
Frankfurt am Main	Dusseldorf	102	Germany	46	Germany	226	9825000000	43	1.28
Hamburg	Copenhagen	17	Germany	17	Denmark	330	14718000000	45	1.87
Hamburg	Berlin	17	Germany	32	Germany	300	13100000000	44	1.70
Hamburg	Bremen	17	Germany	4	Germany	110	4639000000	42	0.62
Hannover	Paris	54	Germany	71	France	703	25197000000	36	3.99
Hannover	Berlin	54	Germany	32	Germany	275	12008000000	44	1.56
Hannover	Bremen	54	Germany	4	Germany	128	5458000000	43	0.73
Hannover	Frankfurt am Main	54	Germany	102	Germany	312	13645000000	44	1.77
Hannover	Hamburg	54	Germany	17	Germany	165	7096000000	43	0.94
Karlsruhe	Paris	117	Germany	71	France	489	16885000000	35	2.77
Karlsruhe	Strasbourg	117	Germany	144	France	73	2661000000	36	0.42
Karlsruhe	Frankfurt am Main	117	Germany	102	Germany	147	6277000000	43	0.83
Kiel	Copenhagen	32	Germany	17	Denmark	404	11817000000	29	2.29
Kiel	Hamburg	32	Germany	17	Germany	110	4639000000	42	0.62

Cologne	Antwerp	53	Germany	11	Belgium	196	6307000000	32	1.11
Cologne	Brussels	53	Germany	32	Belgium	202	6480000000	32	1.14
Cologne	Liege	53	Germany	137	Belgium	116	4161000000	36	0.66
Cologne	Paris	53	Germany	71	France	446	14233000000	32	2.53
Cologne	Aachen	53	Germany	183	Germany	73	3002000000	41	0.42
Cologne	Dusseldorf	53	Germany	46	Germany	43	1637000000	38	0.24
Cologne	Frankfurt am Main	53	Germany	102	Germany	190	8187000000	43	1.08
Leipzig	Prague	113	Germany	195	Czech Republic	245	7221000000	30	1.39
Leipzig	Berlin	113	Germany	32	Germany	171	7369000000	43	0.97
Mannheim	Paris	95	Germany	71	France	508	17492000000	34	2.88
Mannheim	Strasbourg	95	Germany	144	France	128	4870000000	38	0.73
Mannheim	Frankfurt am Main	95	Germany	102	Germany	86	3548000000	41	0.49
Mannheim	Karlsruhe	95	Germany	117	Germany	67	2729000000	41	0.38
Mannheim	Cologne	95	Germany	53	Germany	232	10098000000	43	1.32
Munich	Linz	513	Germany	261	Austria	220	6786000000	31	1.25
Munich	Vienna	513	Germany	213	Austria	373	10212000000	27	2.12
Munich	Salzburg	513	Germany	425	Austria	128	4851000000	38	0.73
Munich	Innsbruck	513	Germany	958	Austria	128	4312000000	34	0.73
Munich	Prague	513	Germany	195	Czech Republic	294	9404000000	32	1.66
Munich	Paris	513	Germany	71	France	703	26870000000	38	3.99
Munich	Strasbourg	513	Germany	144	France	294	12734000000	43	1.66
Munich	Frankfurt am Main	513	Germany	102	Germany	361	15829000000	44	2.05
Munich	Karlsruhe	513	Germany	117	Germany	275	12008000000	44	1.56
Munich	Mannheim	513	Germany	95	Germany	318	13918000000	44	1.80
Ruhr	Antwerp	67	Germany	11	Belgium	220	7184000000	33	1.25
Ruhr	Brussels	67	Germany	32	Belgium	239	7656000000	32	1.35
Ruhr	Liege	67	Germany	137	Belgium	153	5914000000	39	0.87
Ruhr	Lille	67	Germany	27	France	349	10623000000	30	1.98
Ruhr	Aachen	67	Germany	183	Germany	110	4639000000	42	0.62
Ruhr	Bremen	67	Germany	4	Germany	232	10098000000	43	1.32
Ruhr	Dusseldorf	67	Germany	46	Germany	43	1637000000	38	0.24
Ruhr	Frankfurt am Main	67	Germany	102	Germany	226	9825000000	43	1.28
Ruhr	Hamburg	67	Germany	17	Germany	312	13645000000	44	1.77
Ruhr	Hannover	67	Germany	54	Germany	226	9825000000	43	1.28
Ruhr	Cologne	67	Germany	53	Germany	80	3275000000	41	0.45
Ruhr	Mannheim	67	Germany	95	Germany	269	11735000000	44	1.53
Saarbrucken	Paris	370	Germany	71	France	391	13385000000	34	2.22
Saarbrucken	Strasbourg	370	Germany	144	France	110	3742000000	34	0.62
Saarbrucken	Frankfurt am Main	370	Germany	102	Germany	159	6823000000	43	0.90
Saarbrucken	Karlsruhe	370	Germany	117	Germany	122	4442000000	36	0.69
Saarbrucken	Cologne	370	Germany	53	Germany	263	8411000000	32	1.49
Saarbrucken	Mannheim	370	Germany	95	Germany	122	5185000000	42	0.69
Stuttgart	Innsbruck	270	Germany	958	Austria	300	10056000000	34	1.70
Stuttgart	Paris	270	Germany	71	France	538	19130000000	36	3.05
Stuttgart	Strasbourg	270	Germany	144	France	122	4845000000	40	0.69
Stuttgart	Frankfurt am Main	270	Germany	102	Germany	165	7096000000	43	0.94
Stuttgart	Karlsruhe	270	Germany	117	Germany	73	3002000000	41	0.42

Stuttgart	Cologne	270	Germany	53	Germany	342	14700000000	43	1.94
Stuttgart	Mannheim	270	Germany	95	Germany	116	4912000000	42	0.66
Stuttgart	Munich	270	Germany	513	Germany	208	9006000000	43	1.18
Stuttgart	Ruhr	270	Germany	67	Germany	379	16647000000	44	2.15
Stuttgart	Saarbrucken	270	Germany	370	Germany	183	7047000000	38	1.04
Dresden	Prague	138	Germany	195	Czech Republic	135	3264000000	24	0.76
Dresden	Berlin	138	Germany	32	Germany	190	8187000000	43	1.08
Dresden	Leipzig	138	Germany	113	Germany	116	4912000000	42	0.66
Nuremberg	Prague	310	Germany	195	Czech Republic	281	7903000000	28	1.60
Nuremberg	Paris	310	Germany	71	France	709	25883000000	36	4.02
Nuremberg	Frankfurt am Main	310	Germany	102	Germany	214	9279000000	43	1.21
Nuremberg	Mannheim	310	Germany	95	Germany	202	8733000000	43	1.14
Nuremberg	Munich	310	Germany	513	Germany	153	6550000000	43	0.87
Nuremberg	Stuttgart	310	Germany	270	Germany	171	7369000000	43	0.97
Erfurt	Prague	189	Germany	195	Czech Republic	294	9086000000	31	1.66
Erfurt	Berlin	189	Germany	32	Germany	239	10371000000	43	1.35
Erfurt	Frankfurt am Main	189	Germany	102	Germany	214	9279000000	43	1.21
Erfurt	Leipzig	189	Germany	113	Germany	116	4912000000	42	0.66
Thessaloniki	Sofia	51	Greece	536	Bulgaria	251	3882000000	15	1.42
Thessaloniki	Athens	51	Greece	50	Greece	373	6500000000	17	2.12
Budapest	Vienna	119	Hungary	213	Austria	232	3320000000	14	1.32
Budapest	Graz	119	Hungary	425	Austria	306	4160000000	14	1.73
Budapest	Zagreb	119	Hungary	250	Croatia	300	3505000000	12	1.70
Budapest	Brno	119	Hungary	271	Czech Republic	312	4635000000	15	1.77
Budapest	Ostrava	119	Hungary	210	Czech Republic	287	4902000000	17	1.63
Budapest	Prague	119	Hungary	195	Czech Republic	514	8388000000	16	2.91
Brescia	Bologna	122	Italy	49	Italy	165	5797000000	35	0.94
Florence	Bologna	77	Italy	49	Italy	92	3122000000	34	0.52
Genoa	Nice	49	Italy	22	France	190	7387000000	39	1.08
Milan	Innsbruck	124	Italy	958	Austria	330	10814000000	33	1.87
Milan	Grenoble	124	Italy	746	France	324	13357000000	41	1.84
Milan	Lyon	124	Italy	280	France	398	15424000000	39	2.25
Milan	Nice	124	Italy	22	France	257	9838000000	38	1.46
Milan	Paris	124	Italy	71	France	777	26292000000	34	4.40
Milan	Munich	124	Italy	513	Germany	391	13889000000	35	2.22
Milan	Stuttgart	124	Italy	270	Germany	453	16000000000	35	2.57
Milan	Bologna	124	Italy	49	Italy	226	8027000000	35	1.28
Milan	Brescia	124	Italy	122	Italy	92	3122000000	34	0.52
Milan	Florence	124	Italy	77	Italy	281	10034000000	36	1.60
Milan	Genoa	124	Italy	49	Italy	135	4682000000	35	0.76
Rome	Florence	59	Italy	77	Italy	245	8696000000	36	1.39
Rome	Naples	59	Italy	183	Italy	202	7135000000	35	1.14
Turin	Grenoble	242	Italy	746	France	177	8877000000	50	1.01
Turin	Lyon	242	Italy	280	France	300	11499000000	38	1.70
Turin	Nice	242	Italy	22	France	183	6740000000	37	1.04
Turin	Paris	242	Italy	71	France	697	25959000000	37	3.95
Turin	Genoa	242	Italy	49	Italy	153	5351000000	35	0.87

Turin	Milan	242	Italy	124	Italy	141	4905000000	35	0.80
Venice	Bologna	-2	Italy	49	Italy	141	4905000000	35	0.80
Venice	Milan	-2	Italy	124	Italy	257	9142000000	36	1.46
Verona	Bologna	95	Italy	49	Italy	110	3790000000	34	0.62
Verona	Brescia	95	Italy	122	Italy	67	2230000000	33	0.38
Verona	Milan	95	Italy	124	Italy	153	5351000000	35	0.87
Verona	Venice	95	Italy	-2	Italy	110	3790000000	34	0.62
Padua	Bologna	13	Italy	49	Italy	122	4236000000	35	0.69
Padua	Brescia	13	Italy	122	Italy	135	4682000000	35	0.76
Padua	Milan	13	Italy	124	Italy	220	7804000000	35	1.25
Padua	Venice	13	Italy	-2	Italy	43	1338000000	31	0.24
Padua	Verona	13	Italy	95	Italy	73	2453000000	33	0.42
Mediopadana	Bologna	40	Italy	49	Italy	67	2230000000	33	0.38
Mediopadana	Brescia	40	Italy	122	Italy	104	3568000000	34	0.59
Mediopadana	Florence	40	Italy	77	Italy	122	4936000000	35	0.69
Mediopadana	Genoa	40	Italy	49	Italy	153	5351000000	35	0.87
Mediopadana	Milan	40	Italy	124	Italy	165	5797000000	35	0.94
Mediopadana	Verona	40	Italy	95	Italy	98	3345000000	34	0.55
Mediopadana	Padua	40	Italy	13	Italy	122	4236000000	35	0.69
Stretto	Catania	0	Italy	0	Italy	110	3790000000	34	0.62
Trento	Brescia	961	Italy	122	Italy	116	4436000000	38	0.66
Trento	Milan	961	Italy	124	Italy	190	7112000000	38	1.08
Trento	Verona	961	Italy	95	Italy	92	3122000000	34	0.52
Trento	Padua	961	Italy	13	Italy	116	4013000000	35	0.66
Trieste	Zagreb	122	Italy	250	Croatia	183	2740000000	15	1.04
Riga	Tallinn	3	Latvia	39	Estonia	342	1818000000	5	1.94
Riga	Helsinki	3	Latvia	6	Finland	446	13325000000	30	2.53
Vilnius	Helsinki	114	Lithuania	6	Finland	716	14791000000	21	4.06
Vilnius	Riga	114	Lithuania	3	Latvia	312	1667000000	5	1.77
Kaunas	Helsinki	80	Lithuania	6	Finland	722	14821000000	21	4.09
Kaunas	Riga	80	Lithuania	3	Latvia	281	1496000000	5	1.60
Kaunas	Vilnius	80	Lithuania	114	Lithuania	98	509000000	5	0.55
Luxembourg	Brussels	287	Luxembourg	32	Belgium	214	5151000000	24	1.21
Luxembourg	Liege	287	Luxembourg	137	Belgium	116	2633000000	23	0.66
Luxembourg	Paris	287	Luxembourg	71	France	349	10440000000	30	1.98
Luxembourg	Aachen	287	Luxembourg	183	Germany	128	3121000000	24	0.73
Luxembourg	Dusseldorf	287	Luxembourg	46	Germany	196	6123000000	31	1.11
Luxembourg	Frankfurt am Main	287	Luxembourg	102	Germany	208	8348000000	40	1.18
Luxembourg	Cologne	287	Luxembourg	53	Germany	159	4948000000	31	0.90
Luxembourg	Ruhr	287	Luxembourg	67	Germany	232	7760000000	33	1.32
Luxembourg	Saarbrucken	287	Luxembourg	370	Germany	116	3528000000	30	0.66
Amsterdam	Antwerp	0	Netherlands	11	Belgium	165	5059000000	31	0.94
Amsterdam	Brussels	0	Netherlands	32	Belgium	214	6318000000	30	1.21
Amsterdam	Gent	0	Netherlands	1	Belgium	202	6152000000	30	1.14
Amsterdam	Lille	0	Netherlands	27	France	275	8175000000	30	1.56
Amsterdam	Paris	0	Netherlands	71	France	501	15564000000	31	2.84
Amsterdam	Dusseldorf	0	Netherlands	46	Germany	232	8152000000	35	1.32

Amsterdam	Cologne	0	Netherlands	53	Germany	269	9360000000	35	1.53
Amsterdam	Ruhr	0	Netherlands	67	Germany	232	8350000000	36	1.32
Eindhoven	Antwerp	18	Netherlands	11	Belgium	92	2377000000	26	0.52
Eindhoven	Brussels	18	Netherlands	32	Belgium	110	2849000000	26	0.62
Eindhoven	Liege	18	Netherlands	137	Belgium	104	2692000000	26	0.59
Eindhoven	Lille	18	Netherlands	27	France	220	5816000000	26	1.25
Eindhoven	Paris	18	Netherlands	71	France	379	11623000000	31	2.15
Eindhoven	Aachen	18	Netherlands	183	Germany	110	3270000000	30	0.62
Eindhoven	Dusseldorf	18	Netherlands	46	Germany	110	4013000000	36	0.62
Eindhoven	Cologne	18	Netherlands	53	Germany	147	5221000000	36	0.83
Eindhoven	Ruhr	18	Netherlands	67	Germany	135	5105000000	38	0.76
Eindhoven	Amsterdam	18	Netherlands	0	Netherlands	128	4139000000	32	0.73
Groningen	Paris	7	Netherlands	71	France	624	19704000000	32	3.54
Groningen	Ruhr	7	Netherlands	67	Germany	226	8275000000	37	1.28
Groningen	Amsterdam	7	Netherlands	0	Netherlands	171	5588000000	33	0.97
Rotterdam	Antwerp	-4	Netherlands	11	Belgium	104	2989000000	29	0.59
Rotterdam	Brussels	-4	Netherlands	32	Belgium	153	4248000000	28	0.87
Rotterdam	Gent	-4	Netherlands	1	Belgium	141	4082000000	29	0.80
Rotterdam	Lille	-4	Netherlands	27	France	214	6105000000	29	1.21
Rotterdam	Paris	-4	Netherlands	71	France	440	13495000000	31	2.50
Rotterdam	Dusseldorf	-4	Netherlands	46	Germany	220	7441000000	34	1.25
Rotterdam	Cologne	-4	Netherlands	53	Germany	257	8352000000	33	1.46
Rotterdam	Ruhr	-4	Netherlands	67	Germany	220	8002000000	36	1.25
Rotterdam	Amsterdam	-4	Netherlands	0	Netherlands	67	2070000000	31	0.38
Rotterdam	Eindhoven	-4	Netherlands	18	Netherlands	116	3626000000	31	0.66
Utrecht	Antwerp	1	Netherlands	11	Belgium	128	3817000000	30	0.73
Utrecht	Brussels	1	Netherlands	32	Belgium	177	5076000000	29	1.01
Utrecht	Paris	1	Netherlands	71	France	465	14323000000	31	2.64
Utrecht	Dusseldorf	1	Netherlands	46	Germany	190	6704000000	35	1.08
Utrecht	Cologne	1	Netherlands	53	Germany	226	8011000000	35	1.28
Utrecht	Ruhr	1	Netherlands	67	Germany	190	6901000000	36	1.08
Utrecht	Amsterdam	1	Netherlands	0	Netherlands	49	1449000000	30	0.28
Utrecht	Eindhoven	1	Netherlands	18	Netherlands	92	2897000000	32	0.52
Utrecht	Rotterdam	1	Netherlands	-4	Netherlands	61	1863000000	30	0.35
Oslo	Aarhus	40	Norway	24	Denmark	960	22385000000	23	5.45
Oslo	Copenhagen	40	Norway	17	Denmark	654	14572000000	22	3.71
Oslo	Hamburg	40	Norway	17	Germany	972	29197000000	30	5.51
Oslo	Bergen	40	Norway	0	Norway	385	7790000000	20	2.18
Katowice	Vienna	293	Poland	213	Austria	318	5534000000	17	1.80
Katowice	Brno	293	Poland	271	Czech Republic	220	3381000000	15	1.25
Katowice	Ostrava	293	Poland	210	Czech Republic	80	997000000	13	0.45
Katowice	Prague	293	Poland	195	Czech Republic	355	5032000000	14	2.01
Katowice	Budapest	293	Poland	119	Hungary	342	5165000000	15	1.94
Krakow	Vienna	205	Poland	213	Austria	324	5574000000	17	1.84
Krakow	Ostrava	205	Poland	210	Czech Republic	135	1673000000	12	0.76
Krakow	Budapest	205	Poland	119	Hungary	342	4835000000	14	1.94
Krakow	Katowice	205	Poland	293	Poland	73	826000000	11	0.42

Lodz	Katowice	195	Poland	293	Poland	196	2327000000	12	1.11
Lodz	Krakow	195	Poland	205	Poland	202	2402000000	12	1.14
Poznan	Prague	84	Poland	195	Czech Republic	342	4805000000	14	1.94
Poznan	Berlin	84	Poland	32	Germany	263	5230000000	20	1.49
Poznan	Gdansk	84	Poland	-1	Poland	300	3603000000	12	1.70
Poznan	Katowice	84	Poland	293	Poland	324	3903000000	12	1.84
Poznan	Lodz	84	Poland	195	Poland	202	2402000000	12	1.14
Rzeszow	Katowice	200	Poland	293	Poland	226	2702000000	12	1.28
Rzeszow	Krakow	200	Poland	205	Poland	165	1952000000	12	0.94
Rzeszow	Lublin	200	Poland	192	Poland	165	1952000000	12	0.94
Warsaw	Ostrava	121	Poland	210	Czech Republic	367	4525000000	12	2.08
Warsaw	Vilnius	121	Poland	114	Lithuania	428	4212000000	10	2.43
Warsaw	Kaunas	121	Poland	80	Lithuania	422	4178000000	10	2.39
Warsaw	Gdansk	121	Poland	-1	Poland	342	4129000000	12	1.94
Warsaw	Katowice	121	Poland	293	Poland	294	3528000000	12	1.66
Warsaw	Krakow	121	Poland	205	Poland	300	3603000000	12	1.70
Warsaw	Lodz	121	Poland	195	Poland	128	1501000000	12	0.73
Warsaw	Lublin	121	Poland	192	Poland	183	2177000000	12	1.04
Warsaw	Poznan	121	Poland	84	Poland	300	3603000000	12	1.70
Warsaw	Rzeszow	121	Poland	200	Poland	275	3303000000	12	1.56
Wroclaw	Vienna	122	Poland	213	Austria	373	6223000000	17	2.12
Wroclaw	Brno	122	Poland	271	Czech Republic	245	3604000000	15	1.39
Wroclaw	Ostrava	122	Poland	210	Czech Republic	196	2424000000	12	1.11
Wroclaw	Prague	122	Poland	195	Czech Republic	226	3456000000	15	1.28
Wroclaw	Berlin	122	Poland	32	Germany	342	6799000000	20	1.94
Wroclaw	Katowice	122	Poland	293	Poland	190	2252000000	12	1.08
Wroclaw	Krakow	122	Poland	205	Poland	257	3078000000	12	1.46
Wroclaw	Lodz	122	Poland	195	Poland	202	2402000000	12	1.14
Wroclaw	Poznan	122	Poland	84	Poland	165	1952000000	12	0.94
Wroclaw	Warsaw	122	Poland	121	Poland	324	3903000000	12	1.84
Porto	Lisbon	87	Portugal	0	Portugal	294	4929000000	17	1.66
Bucharest	Plovdiv	86	Romania	161	Bulgaria	306	4394000000	14	1.73
Bucharest	Sofia	86	Romania	536	Bulgaria	294	4212000000	14	1.66
Bucharest	Budapest	86	Romania	119	Hungary	648	8764000000	14	3.68
Cluj-Napoca	Budapest	365	Romania	119	Hungary	336	4263000000	13	1.91
Cluj-Napoca	Bucharest	365	Romania	86	Romania	355	5088000000	14	2.01
Iasi	Bucharest	128	Romania	86	Romania	361	5177000000	14	2.05
Timisoara	Budapest	91	Romania	119	Hungary	281	3408000000	12	1.60
Timisoara	Bucharest	91	Romania	86	Romania	391	5624000000	14	2.22
Timisoara	Cluj-Napoca	91	Romania	365	Romania	208	3115000000	15	1.18
Bratislava	Linz	136	Slovakia	261	Austria	220	4800000000	22	1.25
Bratislava	Vienna	136	Slovakia	213	Austria	67	1350000000	20	0.38
Bratislava	Graz	136	Slovakia	425	Austria	208	3384000000	16	1.18
Bratislava	Zagreb	136	Slovakia	250	Croatia	306	3689000000	12	1.73
Bratislava	Brno	136	Slovakia	271	Czech Republic	135	2429000000	18	0.76
Bratislava	Ostrava	136	Slovakia	210	Czech Republic	232	4248000000	18	1.32
Bratislava	Prague	136	Slovakia	195	Czech Republic	336	6182000000	18	1.91

Bratislava	Budapest	136	Slovakia	119	Hungary	183	2206000000	12	1.04
Bratislava	Katowice	136	Slovakia	293	Poland	306	4988000000	16	1.73
Bratislava	Krakow	136	Slovakia	205	Poland	300	4913000000	16	1.70
Kosice	Budapest	199	Slovakia	119	Hungary	214	2567000000	12	1.21
Kosice	Katowice	199	Slovakia	293	Poland	275	3840000000	14	1.56
Kosice	Krakow	199	Slovakia	205	Poland	208	3014000000	14	1.18
Ljubljana	Vienna	312	Slovenia	213	Austria	342	5390000000	16	1.94
Ljubljana	Graz	312	Slovenia	425	Austria	153	2793000000	18	0.87
Ljubljana	Zagreb	312	Slovenia	250	Croatia	116	1745000000	15	0.66
Ljubljana	Venice	312	Slovenia	-2	Italy	196	5282000000	27	1.11
Ljubljana	Trieste	312	Slovenia	122	Italy	80	1287000000	16	0.45
Barcelona	Bordeaux	2	Spain	2	France	477	14791000000	31	2.71
Barcelona	Marseille	2	Spain	17	France	434	13682000000	32	2.46
Barcelona	Montpellier	2	Spain	23	France	306	9251000000	30	1.73
Barcelona	Paris	2	Spain	71	France	911	30139000000	33	5.17
Barcelona	Toulon	2	Spain	258	France	489	15581000000	32	2.77
Barcelona	Toulouse	2	Spain	193	France	287	8812000000	31	1.63
Bilbao	Bordeaux	253	Spain	2	France	312	9752000000	31	1.77
Madrid	Lisbon	669	Spain	0	Portugal	557	11837000000	21	3.16
Madrid	Porto	669	Spain	87	Portugal	410	9320000000	23	2.32
Madrid	Barcelona	669	Spain	2	Spain	575	15128000000	26	3.26
Madrid	Bilbao	669	Spain	253	Spain	349	9109000000	26	1.98
Seville	Lisbon	14	Spain	0	Portugal	330	6685000000	20	1.87
Seville	Madrid	14	Spain	669	Spain	385	10085000000	26	2.18
Valencia	Barcelona	15	Spain	2	Spain	342	8947000000	26	1.94
Valencia	Madrid	15	Spain	669	Spain	324	8459000000	26	1.84
Zaragoza	Barcelona	198	Spain	2	Spain	269	6995000000	26	1.53
Zaragoza	Bilbao	198	Spain	253	Spain	269	6995000000	26	1.53
Zaragoza	Madrid	198	Spain	669	Spain	312	8133000000	26	1.77
Zaragoza	Valencia	198	Spain	15	Spain	257	6669000000	26	1.46
Gothenburg	Aarhus	62	Sweden	24	Denmark	654	16789000000	26	3.71
Gothenburg	Copenhagen	62	Sweden	17	Denmark	349	8976000000	26	1.98
Gothenburg	Bergen	62	Sweden	0	Norway	679	13102000000	19	3.85
Gothenburg	Oslo	62	Sweden	40	Norway	330	5922000000	18	1.87
Stockholm	Copenhagen	14	Sweden	17	Denmark	648	13989000000	22	3.68
Stockholm	Bergen	14	Sweden	0	Norway	832	15463000000	19	4.72
Stockholm	Oslo	14	Sweden	40	Norway	453	7673000000	17	2.57
Stockholm	Gothenburg	14	Sweden	62	Sweden	459	7570000000	17	2.60
Malmo	Aarhus	16	Sweden	24	Denmark	349	11675000000	33	1.98
Malmo	Copenhagen	16	Sweden	17	Denmark	43	3862000000	90	0.24
Malmo	Berlin	16	Sweden	32	Germany	587	28585000000	49	3.33
Malmo	Hamburg	16	Sweden	17	Germany	361	18487000000	51	2.05
Malmo	Kiel	16	Sweden	32	Germany	434	15586000000	36	2.46
Malmo	Oslo	16	Sweden	40	Norway	618	10710000000	17	3.50
Malmo	Gothenburg	16	Sweden	62	Sweden	312	5115000000	16	1.77
Malmo	Stockholm	16	Sweden	14	Sweden	612	10127000000	17	3.47
Basel	Lyon	264	Switzerland	280	France	306	9364000000	31	1.73

Basel	Paris	264	Switzerland	71	France	465	15808000000	34	2.64
Basel	Strasbourg	264	Switzerland	144	France	135	4476000000	33	0.76
Basel	Karlsruhe	264	Switzerland	117	Germany	202	7138000000	35	1.14
Basel	Stuttgart	264	Switzerland	270	Germany	183	7867000000	43	1.04
Basel	Milan	264	Switzerland	124	Italy	330	10668000000	32	1.87
Geneva	Grenoble	406	Switzerland	746	France	135	4414000000	33	0.76
Geneva	Lyon	406	Switzerland	280	France	128	4137000000	32	0.73
Geneva	Paris	406	Switzerland	71	France	489	16619000000	34	2.77
Geneva	Milan	406	Switzerland	124	Italy	300	11577000000	39	1.70
Geneva	Turin	406	Switzerland	242	Italy	214	9340000000	44	1.21
Geneva	Basel	406	Switzerland	264	Switzerland	196	5516000000	28	1.11
Zurich	Innsbruck	428	Switzerland	958	Austria	239	6085000000	26	1.35
Zurich	Lyon	428	Switzerland	280	France	361	10965000000	30	2.05
Zurich	Paris	428	Switzerland	71	France	544	18121000000	33	3.09
Zurich	Strasbourg	428	Switzerland	144	France	165	6385000000	39	0.94
Zurich	Frankfurt am Main	428	Switzerland	102	Germany	349	14261000000	41	1.98
Zurich	Karlsruhe	428	Switzerland	117	Germany	208	8199000000	39	1.18
Zurich	Mannheim	428	Switzerland	95	Germany	269	10713000000	40	1.53
Zurich	Munich	428	Switzerland	513	Germany	294	9022000000	31	1.66
Zurich	Stuttgart	428	Switzerland	270	Germany	190	7380000000	39	1.08
Zurich	Milan	428	Switzerland	124	Italy	263	8711000000	33	1.49
Zurich	Turin	428	Switzerland	242	Italy	294	9939000000	34	1.66
Zurich	Basel	428	Switzerland	264	Switzerland	86	2313000000	27	0.49
Zurich	Geneva	428	Switzerland	406	Switzerland	251	7118000000	28	1.42
Bern	Lyon	498	Switzerland	280	France	263	8118000000	31	1.49
Bern	Paris	498	Switzerland	71	France	508	16888000000	33	2.88
Bern	Strasbourg	498	Switzerland	144	France	208	6583000000	32	1.18
Bern	Stuttgart	498	Switzerland	270	Germany	251	9349000000	37	1.42
Bern	Milan	498	Switzerland	124	Italy	275	9404000000	34	1.56
Bern	Basel	498	Switzerland	264	Switzerland	80	2135000000	27	0.45
Bern	Geneva	498	Switzerland	406	Switzerland	153	4271000000	28	0.87
Bern	Zurich	498	Switzerland	428	Switzerland	104	2847000000	27	0.59
Birmingham	Paris	111	United Kingdom	71	France	587	32113000000	55	3.33
Glasgow	Edinburgh	4	United Kingdom	56	United Kingdom	86	3424000000	40	0.49
Liverpool	Paris	31	United Kingdom	71	France	722	37908000000	53	4.09
Liverpool	Birmingham	31	United Kingdom	111	United Kingdom	141	5795000000	41	0.80
London	Antwerp	9	United Kingdom	11	Belgium	385	22210000000	58	2.18
London	Brussels	9	United Kingdom	32	Belgium	367	21738000000	59	2.08
London	Gent	9	United Kingdom	1	Belgium	330	20794000000	63	1.87
London	Lille	9	United Kingdom	27	France	263	19250000000	73	1.49
London	Paris	9	United Kingdom	71	France	404	24210000000	60	2.29
London	Ruhr	9	United Kingdom	67	Germany	599	29394000000	49	3.40
London	Amsterdam	9	United Kingdom	0	Netherlands	526	26946000000	51	2.98
London	Eindhoven	9	United Kingdom	18	Netherlands	471	24587000000	52	2.67
London	Rotterdam	9	United Kingdom	-4	Netherlands	465	24876000000	54	2.64
London	Utrecht	9	United Kingdom	1	Netherlands	489	25704000000	53	2.77
London	Birmingham	9	United Kingdom	111	United Kingdom	190	7903000000	42	1.08

London	Liverpool	9	United Kingdom	31	United Kingdom	324	13698000000	42	1.84
Manchester	Paris	26	United Kingdom	71	France	685	36327000000	53	3.88
Manchester	Birmingham	26	United Kingdom	111	United Kingdom	122	5005000000	41	0.69
Manchester	Liverpool	26	United Kingdom	31	United Kingdom	61	2371000000	39	0.35
Manchester	London	26	United Kingdom	9	United Kingdom	287	12117000000	42	1.63
Newcastle upon Tyne	Edinburgh	14	United Kingdom	56	United Kingdom	171	7112000000	42	0.97
Newcastle upon Tyne	London	14	United Kingdom	9	United Kingdom	416	17649000000	42	2.36
Newcastle upon Tyne	Manchester	14	United Kingdom	26	United Kingdom	208	8693000000	42	1.18
Leeds	Paris	33	United Kingdom	71	France	673	35801000000	53	3.82
Leeds	Birmingham	33	United Kingdom	111	United Kingdom	177	7376000000	42	1.01
Leeds	Liverpool	33	United Kingdom	31	United Kingdom	128	5268000000	41	0.73
Leeds	London	33	United Kingdom	9	United Kingdom	275	11591000000	42	1.56
Leeds	Manchester	33	United Kingdom	26	United Kingdom	73	2898000000	39	0.42
Leeds	Newcastle upon Tyne	33	United Kingdom	14	United Kingdom	153	6322000000	41	0.87
Nantes	Bordeaux	18	France	2	France	269	9073000000	34	1.53
Naples	Stretto	183	Italy	0	Italy	398	17610000000	44	2.25
Innsbruck	Trento	958	Austria	961	Italy	165	6014000000	36	0.94
Venice	Trieste	-2	Italy	122	Italy	147	4645000000	32	0.83
Erfurt	Nuremberg	189	Germany	310	Germany	202	8733000000	43	1.14
Erfurt	Hannover	189	Germany	54	Germany	214	9279000000	43	1.21
Bremen	Groningen	4	Germany	7	Netherlands	159	6328000000	40	0.90
Kosice	Cluj-Napoca	199	Slovakia	365	Romania	306	4017000000	13	1.73
Timisoara	Sofia	119	Hungary	536	Bulgaria	679	9224000000	14	3.85
Naples	Bari	183	Italy	0	Italy	232	8250000000	36	1.32
Palermo	Catania	35	Italy	0	Italy	177	6243000000	35	1.01
Stretto	Palermo	0	Italy	35	Italy	226	10522000000	47	1.28
Genoa	Florence	49	Italy	124	Italy	135	4682000000	35	0.76
Berlin	Munich	32	Germany	513	Germany	673	17444000000	26	3.82
Berlin	Amsterdam	32	Germany	0	Netherlands	636	25900000000	41	3.61
Berlin	Warsaw	32	Germany	121	Poland	550	8758000000	16	3.12
Berlin	Paris	32	Germany	71	France	972	37205000000	38	5.51
Vilnius	Tallinn	114	Lithuania	39	Estonia	612	3286000000	5	3.47

APPENDIX E – Trip generation

City	Population	GDPpc	Trips
Linz	651950	50561.96	6827191
Vienna	2983513	49808.19	30777442
Salzburg	375489	59559.95	4631859
Graz	657316	47904.99	6521670
Innsbruck	352507	49916.25	3644295
Antwerp	1139663	51438.09	12141299
Brussels	3284548	55818.75	37971659
Gent	645813	47612.05	6368359
Liege	793118	31800.61	5223687
Plovdiv	536672	16082.94	1787633
Sofia	1553106	38906.12	12514768
Zagreb	1217131	34530.82	8704585
Brno	731860	32740.15	4962638
Ostrava	711860	26886.78	3964032
Prague	2231212	58047.93	26824486
Aarhus	521123	41760.46	4507227
Copenhagen	1933919	56747.57	22729476
Tallinn	390860	44055.73	3566379
Helsinki	1507140	53141.24	16587812

Tampere	444370	37469.12	3448435
Bordeaux	1277949	37992.47	10055761
Grenoble	670721	35755.26	4966903
Lille	1518544	32923.24	10354611
Lyon	2113104	48478.36	21216447
Marseille	1284351	38455.1	10229197
Montpellier	729272	31917.61	4820851
Nantes	989758	38759.65	7945344
Nice	1018815	39058.84	8241732
Paris	12924097	62665.25	1.68E+08
Rennes	697990	37975.51	5489801
Rouen	699493	33560.02	4861938
Strasbourg	824733	37209.23	6355765
Toulon	570893	26653.68	3151488
Toulouse	1423458	43505.58	12826066
Aachen	554910	42461.55	4880027
Berlin	5303922	41572.02	45666959
Bremen	1274968	42407.96	11198259
Dusseldorf	1554077	63622.66	20478031
Frankfurt am Main	2710501	61956.13	34780653
Hamburg	3315036	54530.9	37439907
Hannover	1316467	48965.99	13350834
Karlsruhe	756983	54229.93	8502154
Kiel	647622	38655.15	5184810
Cologne	2002550	53862.86	22339664
Leipzig	1043613	36703.73	7933294
Mannheim	1187725	49980.56	12294782
Munich	2907752	74989.14	45160589
Ruhr	5115088	36452.77	38617797
Saarbrucken	800222	40369.91	6690708
Stuttgart	2787449	60412.86	34877083
Dresden	1343213	35515.91	9880335
Nuremberg	1348820	53943.24	15069362
Erfurt	527548	36366.14	3973407
Athens	3530371	34455.8	25193384
Thessaloniki	1050568	21380.81	4652134
Budapest	2997506	43878	27240230
Dublin	1971242	90634.47	37003021
Bari	729385	25950.81	3920230
Bologna	786352	48674.84	7927302
Brescia	477619	40216.29	3978208
Catania	635614	22143.52	2915036
Florence	794659	49373.25	8125991
Genoa	692806	42541.93	6104255
Milan	4965808	54597.88	56152562
Naples	3362207	23177.73	16139840
Palermo	1001778	21998.84	4564310

Rome	4335555	44733.59	40168196
Turin	1733674	38849.85	13949564
Venice	557748	35439.1	4093781
Verona	515613	39772.42	4247269
Padua	534896	40202	4453699
Mediopadana	678542	43631.81	6131740
Stretto	1116013	18314.8	4233264
Trento	239900	34245.03	1701499
Trieste	232405	30365.4	1461599
Riga	930245	35310.49	6803071
Vilnius	528471	45571.32	4987887
Kaunas	288575	31705.05	1894921
Luxembourg	610825	100154.9	12670476
Amsterdam	2862590	65254.35	38687661
Eindhoven	760059	55961.65	8809305
Groningen	478761	46075.92	4568742
Rotterdam	1860582	48924.02	18852753
Utrecht	898712	59893.07	11148103
Bergen	419854	45632.94	3968082
Oslo	1398715	59952.02	17367483
Gdansk	1161208	35053.28	8430291
Katowice	2496193	31352.28	16208808
Krakow	1410424	36367.93	10623609
Lodz	907836	33596.64	6316944
Lublin	670334	25660.55	3562551
Poznan	988374	46359.93	9490037
Rzeszow	505486	24861.22	2602768
Warsaw	3181548	60725.44	40014096
Wroclaw	877966	44071.81	8013872
Lisbon	3008000	37834.4	23570483
Porto	1280190	27988.86	7421018
Bucharest	2212830	57195.91	26213009
Cluj-Napoca	383849	33212.6	2640385
Iasi	393605	19042.68	1552360
Timisoara	351851	30997.71	2258876
Bratislava	440611	69176.85	6312770
Kosice	367712	10496.6	799393.3
Ljubljana	292988	46196.49	2803255
Barcelona	5034925	40203.79	41924110
Bilbao	1007915	41130.83	8586085
Madrid	6882461	45565.96	64951346
Seville	1549641	26796.57	8600312
Valencia	1748142	29981.37	10855054
Zaragoza	768643	37187.79	5920098
Gothenburg	1037675	44287.04	9517916
Stockholm	2344124	63365.45	30763583
Malmo	680335	39642.03	5585764

Basel	550152	84689.1	9649706
Geneva	597269	74794.45	9252161
Zurich	1384728	71832.93	20601170
Bern	419983	57060.16	4963277
Birmingham	3116866	32090.87	20715884
Edinburgh	907580	48229.19	9065645
Glasgow	1845020	35425.7	13537031
Liverpool	1544216	30141.23	9639908
London	12396541	62394.65	1.6E+08
Manchester	3383986	37244.06	26102937
Newcastle upon Tyne	1186198	29965.29	7361724
Leeds	2641062	33928.87	18558883

APPENDIX F – National Values of Time (VOT)

Country	PLI Index	VOT In-Vehicle	VOT Access/Egress	VOT Waiting
Austria	1.13	56	76	84
Belgium	1.15	57	77	85
Bulgaria	0.54	27	36	40
Croatia	0.71	35	48	53
Czech Republic	0.75	37	51	56
Denmark	1.44	71	97	107
Estonia	0.85	42	57	63
Europe	1.00	49	67	74
Finland	1.26	63	85	94
France	1.14	56	76	84
Germany	1.07	53	72	80
Greece	0.87	43	58	65
Hungary	0.67	33	45	50
Ireland	1.36	68	92	101
Italy	1.02	50	68	75
Latvia	0.78	39	52	58
Lithuania	0.68	34	46	50
Luxembourg	1.32	65	89	98
Netherlands	1.17	58	79	87
Norway	1.45	72	97	107
Poland	0.60	30	40	44
Portugal	0.88	43	59	65
Romania	0.56	27	37	41
Slovakia	0.86	43	58	64
Slovenia	0.87	43	58	65
Spain	0.96	48	65	71
Sweden	1.23	61	83	91
Switzerland	1.65	82	111	122
United Kingdom	1.21	60	81	90

APPENDIX G – National Budget Contributions

Country	GDP	Yearly Budget Contribution
Austria	397169500000	283572894
Belgium	478676100000	341767348
Bulgaria	61558500000	43951819
Croatia	55644400000	39729243
Czech Republic	225613500000	161084557
Denmark	309526400000	220997073
Estonia	27764700000	19823567
Europe	239858000000	171254910
Finland	2437635000000	1740433771
France	3473260000000	2479854038
Germany	183351200000	130909927
Greece	146554500000	104637651
Hungary	356704600000	254681579
Ireland	1796648500000	1282779302
Italy	30678600000	21904047
Latvia	48916400000	34925555
Lithuania	62373600000	44533788
Luxembourg	813055000000	580508722
Netherlands	365130500000	260697542
Norway	532504700000	380200138
Poland	214374600000	153060156
Portugal	224178600000	160060061
Romania	94428300000	67420349
Slovakia	48533100000	34651884
Slovenia	1245513000000	889277060
Spain	476869500000	340477464
Sweden	644443200000	460122499
Switzerland	2526615200000	1803964260
United Kingdom	397169500000	283572894

APPENDIX H - Scenario Investment Sequence & Base Network

I Base Network Infrastructure

City1	City2	Country1	Country2	Distance	Travel Time
Innsbruck	Trento	Austria	Italy	165	0.936409
Antwerp	Rotterdam	Netherlands	Belgium	104	0.589591
Brussels	Liege	Belgium	Belgium	104	0.589591
Brussels	Lille	France	Belgium	116	0.658955
Liege	Aachen	Germany	Belgium	49	0.277455
Copenhagen	Hamburg	Germany	Denmark	330	1.872818
Copenhagen	Malmo	Sweden	Denmark	43	0.242773
Tallinn	Riga	Latvia	Estonia	342	1.942182
Bordeaux	Paris	France	France	550	3.121364
Bordeaux	Toulouse	France	France	239	1.352591
Grenoble	Turin	Italy	France	177	1.005773
Lille	Paris	France	France	245	1.387273
Lille	London	United Kingdom	France	263	1.491318
Lyon	Marseille	France	France	300	1.699409
Lyon	Montpellier	France	France	281	1.595364
Lyon	Paris	France	France	434	2.462409
Marseille	Montpellier	France	France	135	0.763
Montpellier	Barcelona	Spain	France	306	1.734091
Paris	Rennes	France	France	367	2.080909
Paris	Strasbourg	France	France	422	2.393045
Berlin	Hannover	Germany	Germany	275	1.560682
Frankfurt am Main	Hannover	Germany	Germany	312	1.768773
Frankfurt am Main	Cologne	Germany	Germany	190	1.075136
Leipzig	Erfurt	Germany	Germany	116	0.658955
Mannheim	Stuttgart	Germany	Germany	116	0.658955
Nuremberg	Erfurt	Germany	Germany	202	1.1445
Bari	Naples	Italy	Italy	232	1.317909
Bologna	Florence	Italy	Italy	92	0.520227
Bologna	Mediopadana	Italy	Italy	67	0.3815
Brescia	Milan	Italy	Italy	92	0.520227
Brescia	Verona	Italy	Italy	67	0.3815
Florence	Rome	Italy	Italy	245	1.387273
Milan	Turin	Italy	Italy	141	0.797682
Milan	Mediopadana	Italy	Italy	165	0.936409
Naples	Rome	Italy	Italy	202	1.1445
Naples	Stretto	Italy	Italy	398	2.254318
Venice	Padua	Italy	Italy	43	0.242773
Verona	Padua	Italy	Italy	73	0.416182
Riga	Kaunas	Lithuania	Latvia	281	1.595364
Vilnius	Kaunas	Lithuania	Lithuania	98	0.554909

Amsterdam	Rotterdam	Netherlands	Netherlands	67	0.3815
Lisbon	Madrid	Spain	Portugal	557	3.156045
Barcelona	Zaragoza	Spain	Spain	269	1.526
Bilbao	Madrid	Spain	Spain	349	1.976864
Madrid	Seville	Spain	Spain	385	2.184955
Madrid	Valencia	Spain	Spain	324	1.838136
Madrid	Zaragoza	Spain	Spain	312	1.768773
Birmingham	London	United Kingdom	United Kingdom	190	1.075136
Birmingham	Manchester	United Kingdom	United Kingdom	122	0.693636
Innsbruck	Trento	Austria	Italy	165	0.936409
Antwerp	Rotterdam	Netherlands	Belgium	104	0.589591
Brussels	Liege	Belgium	Belgium	104	0.589591
Brussels	Lille	France	Belgium	116	0.658955
Liege	Aachen	Germany	Belgium	49	0.277455
Copenhagen	Hamburg	Germany	Denmark	330	1.872818
Copenhagen	Malmo	Sweden	Denmark	43	0.242773
Tallinn	Riga	Latvia	Estonia	342	1.942182
Bordeaux	Paris	France	France	550	3.121364
Bordeaux	Toulouse	France	France	239	1.352591
Grenoble	Turin	Italy	France	177	1.005773
Lille	Paris	France	France	245	1.387273
Lille	London	United Kingdom	France	263	1.491318
Lyon	Marseille	France	France	300	1.699409
Lyon	Montpellier	France	France	281	1.595364
Lyon	Paris	France	France	434	2.462409
Marseille	Montpellier	France	France	135	0.763
Montpellier	Barcelona	Spain	France	306	1.734091
Paris	Rennes	France	France	367	2.080909
Paris	Strasbourg	France	France	422	2.393045
Berlin	Hannover	Germany	Germany	275	1.560682
Frankfurt am Main	Hannover	Germany	Germany	312	1.768773
Frankfurt am Main	Cologne	Germany	Germany	190	1.075136
Leipzig	Erfurt	Germany	Germany	116	0.658955
Mannheim	Stuttgart	Germany	Germany	116	0.658955
Nuremberg	Erfurt	Germany	Germany	202	1.1445
Bari	Naples	Italy	Italy	232	1.317909
Bologna	Florence	Italy	Italy	92	0.520227
Bologna	Mediopadana	Italy	Italy	67	0.3815
Brescia	Milan	Italy	Italy	92	0.520227
Brescia	Verona	Italy	Italy	67	0.3815
Florence	Rome	Italy	Italy	245	1.387273
Milan	Turin	Italy	Italy	141	0.797682
Milan	Mediopadana	Italy	Italy	165	0.936409
Naples	Rome	Italy	Italy	202	1.1445
Naples	Stretto	Italy	Italy	398	2.254318
Venice	Padua	Italy	Italy	43	0.242773
Verona	Padua	Italy	Italy	73	0.416182

Riga	Kaunas	Lithuania	Latvia	281	1.595364
Vilnius	Kaunas	Lithuania	Lithuania	98	0.554909
Amsterdam	Rotterdam	Netherlands	Netherlands	67	0.3815
Lisbon	Madrid	Spain	Portugal	557	3.156045
Barcelona	Zaragoza	Spain	Spain	269	1.526
Bilbao	Madrid	Spain	Spain	349	1.976864
Madrid	Seville	Spain	Spain	385	2.184955
Madrid	Valencia	Spain	Spain	324	1.838136
Madrid	Zaragoza	Spain	Spain	312	1.768773
Birmingham	London	United Kingdom	United Kingdom	190	1.075136
Birmingham	Manchester	United Kingdom	United Kingdom	122	0.693636

I Scenario Infrastructural Investment Sequence

Candidate Investment	City1	City2	NPV	Investment	BCR	Investment Year	Construction Year
['Brussels', 'Antwerp']	Brussels	Antwerp	9812209891	1259000000	12.34	2023	2038
['Leeds', 'Manchester']	Leeds	Manchester	14935100538	2898000000	8.50	2023	2038
['Ruhr', 'Dusseldorf']	Ruhr	Dusseldorf	5792885770	1637000000	6.15	2023	2038
['Cologne', 'Dusseldorf']	Cologne	Dusseldorf	6502916208	1637000000	6.78	2023	2038
['Mannheim', 'Frankfurt am Main']	Mannheim	Frankfurt am Main	10729058402	3548000000	5.40	2023	2038
['Krakow', 'Katowice']	Krakow	Katowice	2316140001	826000000	5.08	2023	2038
['Luxembourg', 'Liege']	Luxembourg	Liege	7080342357	2633000000	4.91	2024	2039
['Cologne', 'Aachen']	Cologne	Aachen	8194276719	3002000000	4.97	2024	2039
['Stockholm', 'Gothenburg']	Stockholm	Gothenburg	17917030647	7570000000	4.44	2024	2039
['Leeds', 'Newcastle upon Tyne']	Leeds	Newcastle upon Tyne	13833266212	6322000000	4.18	2025	2040
['Newcastle upon Tyne', 'Edinburgh']	Newcastle upon Tyne	Edinburgh	15897823083	7112000000	4.25	2026	2041
['Utrecht', 'Amsterdam']	Utrecht	Amsterdam	3373300750	1449000000	4.39	2026	2041
['Thessaloniki', 'Athens']	Thessaloniki	Athens	13138709138	6500000000	3.94	2026	2041
['Budapest', 'Bratislava', 'Vienna']	Budapest	Bratislava	6762934339	2206000000	3.77	2026	2041
['Budapest', 'Bratislava', 'Vienna']	Bratislava	Vienna	6762934339	1350000000	3.77	2026	2041
['Porto', 'Lisbon']	Porto	Lisbon	9616458950	4929000000	3.84	2027	2042
['Stuttgart', 'Munich']	Stuttgart	Munich	16455809089	9006000000	3.66	2028	2043
['Warsaw', 'Lodz']	Warsaw	Lodz	2779043837	1501000000	3.69	2028	2043
['Lodz', 'Katowice']	Lodz	Katowice	7046857908	2327000000	5.41	2028	2043
['Tampere', 'Helsinki']	Tampere	Helsinki	3039695321	1821000000	3.43	2028	2043
['Lyon', 'Grenoble']	Lyon	Grenoble	6238479043	3798000000	3.39	2028	2043
['Leeds', 'London']	Leeds	London	17837200100	11591000000	3.24	2029	2044
['Glasgow', 'Edinburgh']	Glasgow	Edinburgh	5396878063	3424000000	3.29	2030	2045
['Manchester', 'Liverpool']	Manchester	Liverpool	3438240767	2371000000	3.11	2030	2045
['Vienna', 'Linz']	Vienna	Linz	4777960163	3450000000	3.02	2030	2045
['Salzburg', 'Linz']	Salzburg	Linz	4392450585	2484000000	3.57	2030	2045
['Graz', 'Vienna']	Graz	Vienna	5151492484	3384000000	3.22	2030	2045
['Prague', 'Brno', 'Vienna']	Prague	Brno	9246427659	3753000000	3.11	2031	2046
['Prague', 'Brno', 'Vienna']	Brno	Vienna	9246427659	2619000000	3.11	2031	2046

['Katowice', 'Ostrava', 'Brno']	Katowice	Ostrava	7063094121	997000000	3.85	2031	2046
['Katowice', 'Ostrava', 'Brno']	Ostrava	Brno	7063094121	2615000000	3.85	2031	2046
['Munich', 'Salzburg']	Munich	Salzburg	7261928028	4851000000	3.18	2032	2047
['Poznan', 'Lodz']	Poznan	Lodz	3637689825	2402000000	3.20	2032	2047
['Zurich', 'Stuttgart']	Zurich	Stuttgart	10500757175	7380000000	3.07	2032	2047
['Rennes', 'Nantes']	Rennes	Nantes	5467509282	3798000000	3.10	2033	2048
['Hannover', 'Hamburg']	Hannover	Hamburg	9693501108	7096000000	2.99	2033	2048
['Stuttgart', 'Karlsruhe', 'Strasbourg']	Stuttgart	Karlsruhe	7201746800	3002000000	2.85	2034	2049
['Stuttgart', 'Karlsruhe', 'Strasbourg']	Karlsruhe	Strasbourg	7201746800	2661000000	2.85	2034	2049
['Geneva', 'Lyon']	Geneva	Lyon	5115517266	4137000000	2.80	2034	2049
['Bern', 'Zurich']	Bern	Zurich	3433790244	2847000000	2.76	2034	2049
['Ruhr', 'Hannover']	Ruhr	Hannover	10252193562	9825000000	2.52	2035	2050
['Dusseldorf', 'Aachen']	Dusseldorf	Aachen	3915698821	3002000000	2.90	2035	2050
['Zagreb', 'Graz']	Zagreb	Graz	2573316371	2416000000	2.55	2036	2051
['Munich', 'Innsbruck']	Munich	Innsbruck	4134563620	4312000000	2.40	2036	2051
['Trento', 'Verona']	Trento	Verona	3485812061	3122000000	2.63	2036	2051
['Warsaw', 'Gdansk']	Warsaw	Gdansk	4124872088	4129000000	2.45	2036	2051
['Oslo', 'Bergen']	Oslo	Bergen	6859051181	7790000000	2.28	2037	2052
['Bucharest', 'Sofia']	Bucharest	Sofia	3668712376	4212000000	2.27	2037	2052
['Stockholm', 'Oslo']	Stockholm	Oslo	6525435773	7673000000	2.24	2038	2053
['Luxembourg', 'Saarbrucken']	Luxembourg	Saarbrucken	2846788619	3528000000	2.17	2038	2053
['Saarbrucken', 'Karlsruhe']	Saarbrucken	Karlsruhe	7662903147	4442000000	3.51	2039	2054
['Toulon', 'Marseille']	Toulon	Marseille	1713123948	1899000000	2.31	2039	2054
['Geneva', 'Bern', 'Basel']	Geneva	Bern	4912465308	4271000000	2.12	2039	2054
['Geneva', 'Bern', 'Basel']	Bern	Basel	4912465308	2135000000	2.12	2039	2054
['Wroclaw', 'Lodz']	Wroclaw	Lodz	1852454822	2402000000	2.12	2040	2055
['Basel', 'Strasbourg']	Basel	Strasbourg	3285673014	4476000000	2.07	2040	2055
['Mannheim', 'Karlsruhe']	Mannheim	Karlsruhe	2419579657	2729000000	2.29	2040	2055
['Leipzig', 'Berlin']	Leipzig	Berlin	5344007097	7369000000	2.06	2041	2056
['Nuremberg', 'Stuttgart']	Nuremberg	Stuttgart	7554861181	7369000000	2.49	2041	2056
['Warsaw', 'Lublin']	Warsaw	Lublin	1912573565	2177000000	2.28	2041	2056
['Leipzig', 'Dresden', 'Prague']	Leipzig	Dresden	6232493442	4912000000	2.11	2042	2057
['Leipzig', 'Dresden', 'Prague']	Dresden	Prague	6232493442	3264000000	2.11	2042	2057
['Zurich', 'Milan']	Zurich	Milan	6459712076	8711000000	2.08	2043	2058
['Zurich', 'Basel']	Zurich	Basel	2182159729	2313000000	2.37	2043	2058
['Thessaloniki', 'Sofia']	Thessaloniki	Sofia	2484222790	3882000000	1.93	2043	2058
['Nuremberg', 'Munich']	Nuremberg	Munich	3349298275	6550000000	1.74	2044	2059
['Erfurt', 'Hannover']	Erfurt	Hannover	5690861442	9279000000	1.89	2045	2060
['Saarbrucken', 'Strasbourg']	Saarbrucken	Strasbourg	1720936707	3742000000	1.67	2045	2060
['Verona', 'Bologna']	Verona	Bologna	1758701832	3790000000	1.68	2045	2060
['Bratislava', 'Brno']	Bratislava	Brno	1143080810	2429000000	1.68	2045	2060
['Toulon', 'Nice']	Toulon	Nice	1854411298	4431000000	1.61	2046	2061
['Milan', 'Genoa']	Milan	Genoa	1773850414	4682000000	1.55	2046	2061
['Genoa', 'Florence']	Genoa	Florence	9552754552	4682000000	3.97	2046	2061
['Groningen', 'Amsterdam']	Groningen	Amsterdam	1834827789	5588000000	1.48	2047	2062
['Nuremberg', 'Prague']	Nuremberg	Prague	2278789106	7903000000	1.42	2048	2063
['Wroclaw', 'Prague']	Wroclaw	Prague	1380340587	3456000000	1.58	2048	2063

['Gent', 'Antwerp']	Gent	Antwerp	611304343	1417000000	1.63	2048	2063
['Lille', 'Gent']	Lille	Gent	5053986283	2023000000	4.64	2048	2063
['Nuremberg', 'Frankfurt am Main']	Nuremberg	Frankfurt am Main	2939285998	9279000000	1.46	2049	2064
['Utrecht', 'Eindhoven']	Utrecht	Eindhoven	743114043	2897000000	1.37	2049	2064
['Eindhoven', 'Liege']	Eindhoven	Liege	644908098	2692000000	1.35	2049	2064
['Ljubljana', 'Zagreb']	Ljubljana	Zagreb	386934151	1745000000	1.32	2049	2064
['Zurich', 'Strasbourg']	Zurich	Strasbourg	1140472741	6385000000	1.26	2050	2065
['Wroclaw', 'Poznan']	Wroclaw	Poznan	398409541	1952000000	1.30	2050	2065
['Wroclaw', 'Katowice']	Wroclaw	Katowice	614604837	2252000000	1.40	2050	2065

APPENDIX I – Model Validation

II Infrastructural Geospatial Conformations

This sub Section aims at providing more graphical insight on the modelling ability regarding HSR line design with the use of the hexagonal indexing system used for this work.

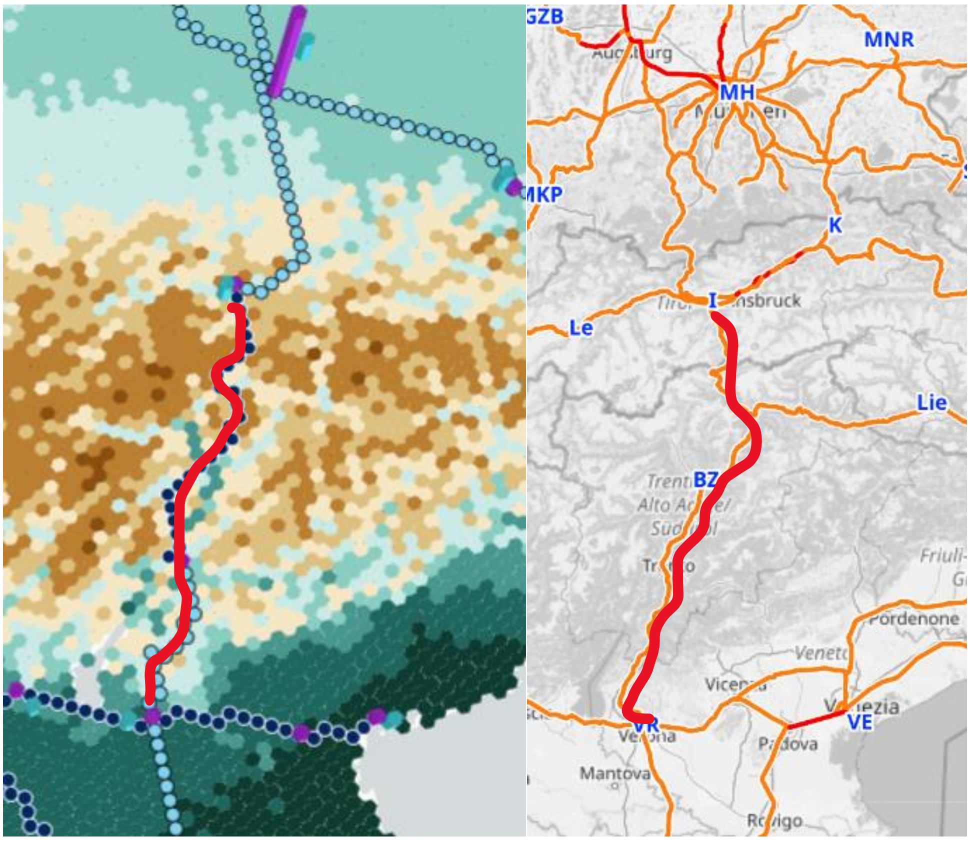


Figure 53 - Brenner line (Verona-Innsbruck)

III Infrastructural Costs

The following example in Table 19 can increase the insight in what could be the cost per kilometre implications for a know group of HSR lines.

Table 23 - Cost comparison of selected example countries

Country	Surface ml/pkm	Underground ml/pkm	Reference project (Adjusted for inflation 2019)	Cost components
Netherlands	55	160	HSL Zuid: 65 ml/km (Infrasite, 2023)	Plain, population density, viaducts and tunnel
Italy	30	88	Verona-Padova: 62 ml/km (IRICAVDUE, 2023)	Plain, High population density
France	21	62	LGV Mediterranean: 20 ml/km (OECD, 2013)	Plain and river basin, medium population density
Spain	23	66	Madrid – Valencia: 19 ml/km (EIB, 2008).	Surface, low population density
Germany	24	70	Stuttgart-Ulm: 33 ml/km (Der Spiegel, 2010)	Hilly, low population density, high tunnel %

UK	32	92	HS 2: 116 ml/km (HS2, 2023), double cost overruns due to inflation and material costs (Reuters, 2020)	Hilly, very high population density
Estonia	10	30	Rail Baltica: 7 ml/pkm (Rail Baltica, 2023)	Plain, very low population density

Some accuracy analyses have been conducted against existing lines in terms of costs and distance, to assess the validity of the modelled HSR connections. Table 21 provides a comparison between 10 existing lines. If the average accuracy is below 100% it means that the model underestimates that parameter for that specific line. Oppositely, the model overestimates the parameter value for that specific line.

Table 24 - Existing HSR lines compared to modelled ones, accuracy analysis

Origin	Destination	Real Cost (bn€)	Model Cost (bn€)	Accuracy Cost	Real Length (km)	Model Lenght (km)	Accuracy Distance
Turin	Lyon	25000	7802	31%	271	343	127%
Madrid	Barcelona	10893	13000	119%	649	658	101%
London	Paris	19600	19677	100%	467	462	99%
Seville	Madrid	6193	8667	140%	471	441	94%
Rotterdam	Amsterdam	6560	3384	52%	70	77	110%
Milan	Bologna	6734	6698	99%	220	259	118%
Paris	Strasbourg	8231	8868	108%	457	483	106%
Cologne	Frankfurt am Main	6560	4466	68%	180	217	121%
Rome	Naples	6396	5954	93%	205	231	113%
Florence	Bologna	4360	2605	60%	78	105	135%
Average Modelling Accuracy		Costs	87%		Distance	112%	

From table 21 it can be concluded that on average and based on existing lines, the model underestimates costs, and overestimates distances compared to real case scenarios. This behaviour could be mainly attributed to the hexagonal indexing properties, which are not able to fully grasp topographical characteristics. In relation to costs, this means that tunnels and bridges are not fully accounted in the cost calculations due to low resolution values of the hexagon. In terms of distance, by directly connecting the centroids of the hexagons, it is not considered that HSR lines merge with conventional rail networks usually outside the cities. This therefore leads to overestimating line length.