The long-distance European rail network under operator competition

A Transit Network Design and Frequency Setting problem approach

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TU Delft

3MARS

Lab Smart Public Transport

The long-distance European rail network under operator competition

by

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To obtain the degree of Master of Science in
Transport, Infrastructure & Logistics at Delft
University of Technology

February 2026 – November 2026

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Cover image: Station of Basel SBB on a summer morning, picture by author.
An electronic version of this thesis is available at http://repository.tudelft.nl/
The data and code underlying this thesis is available at https://data.4tu.nl

Acknowledgements

“TIL students are just like normal people. The only difference is that the chances of them randomly bringing up trains during a conversation nears 100%.”

Nearly three years ago, in December of 2023, I applied, somewhat on a whim, for the Transport, Infrastructure and Logistics masters at TU Delft. I had no clue if I would make it in, no idea how I would fare if I would make it in, and even when I received the acceptance letter, I was questioning how things would go, academically and socially. New country, by myself for the first time, new people, different studies. Fast forward to now, and it was without a doubt one of the best decisions in my life. These two- and a-bit years in Delft have been a fantastic experience, filled with many highs and some lows. I tested the first experiences of living on my own, enjoyed the time at university where I found the curriculum challenging at first, but interesting, and took in the places in this new country. To end, came this thesis. At times, it ended up reminding me of why I was in doubt about my abilities before coming here. But, in the end, despite its challenges, frustrations and demoralizing delays, it remained an interesting project, and something I am proud to have done, even if I am not fully happy with how everything turned out.

Above all, my time in Delft was marked by its people. Through the classes and especially Dispuut Verkeer and TIL-Ballen I got to meet people from all over the globe with similar interests as me. With these people, I got to sit through classes, suffer through exams, unwind at the HoK when we should have been working, wait in line at PSOR for drinks, play Football, participate in and then plan all kinds of activities such as a Mario Kart tournament or a simple barbecue-that-turned-out-not-to-be-one-due-to-red-heat-alert, and travel the world in a total of five tours that took us all the way to China and South Korea.

To Luke, John, Nicholas, Oskar, Moritz, Hugo, Martijn, Thomas, Mika and so many others in DV and TIL-Ballen: Thank you from the bottom of my heart. From the introduction period to the study tour, through the classes, exams, football games, activities of all sorts, V-Drinks, hangouts at the HoK, movie nights and trips, you made my time in Delft unforgettable, and I will look back fondly on these memories. To Thomas, Osman, Guillaume (both of them), Seth, Brie, Leon and Cathal, thank you for being here nearly every evening, even if only through a screen most of the time. The gaming sessions with you were an integral part of my life outside of the university hours, and seeing most of you irl at various points of these two years made it even more special, may it have been showing you around Delft, LANing it out in Paris or pulling an all-nighter after 10 hours of metal and pouring rain. To the one in Delft that made it to more than friends: Mari, thank you for all of the love you have given me for these past 9 months, and continue to give me as I write these words. You helped me get through the thesis, even after the delays and frustrations and kept me grounded through it all. It helped me so much to spend time with you, may it have been stargazing, going to see a flower parade, eating Brazilian desserts or simply working on our theses side by side. Last but certainly not least my family: despite the distance you were always there for me, supported and loved me, and every single time I went to your place after months in Delft, going through a 12-hour night train journey (of which about 2 were spent sleeping), I felt back home the moment I stepped through the door. From the bottom of my heart: Merci.

With love, Sam

Summary

With increased numbers of long-distance travel in the context of climate change, passenger rail transport is seen as a sustainable and viable alternative for European policymakers due to its lower environmental externalities compared to air and road travel. To increase the competitiveness of the mode and the quality of its services, the European Commission introduced a series railway packages aimed at opening the passenger rail market to competition between operators, removing barriers of entry and reducing costs of authorisations and certifications. This type of on-track operator competition already exists in a few countries such as Italy, the Czech Republic and Spain, and is further expected to be expanded in markets such as Germany and the channel tunnel to London. These developments make it thus relevant to investigate how competition between operators can shape the European long-distance rail line network.

Existing empirical studies in countries such as Austria, Italy, and the Czech Republic find that generally, rail markets where competition between operators takes place have increased frequencies, lower ticket prices and more diversified services, which leads to an increase in ridership. Competition however also leads to profitability losses for operators, which incentivises monopolisation, or forces incumbent operators to reduce services on other parts of the network to remain competitive on the profitable lines, which can lead to a net negative in welfare.

Game-theoretic models are used to reproduce these findings and test for various types of policies and competition for single-lines or small networks. Existing literature in network planning problem fields such as the Transit Network Design and Frequency Setting Problem (TNDFSP) methods have been applied to larger networks but exclusively use a central planner/single operator perspective. This means there is a gap to fill by using these TNDFSP methodologies to simulate line planning and frequency setting on a European network with multiple operators competing for passenger demand.

The main research question this thesis attempts to answer is: *how does a decentralised European long-distance rail network perform given competition between service providers?* To answer this, a customised TNDFSP methodology with competition between self-centred operators is developed and applied on a European rail network dataset. First, a pool of viable lines is generated between the nodes, using demand-weighted shortest-path methods. Then, in an iterative fashion, every operator solves a Mixed-Integer Linear Program (MILP) that selects lines from this line pool and sets daily frequencies on them, taking the plans of its competitors from the previous iteration and an estimate of the expected demand per line as inputs. Elastic passenger demand is then assigned to the network in a capacity-constrained probabilistic manner using a multinomial logit route choice model. This is repeated until a convergence is reached, which is either at a maximum of 50 iterations, the network does not change, or an ε-equilibrium is reached where objective values of the operators change by less than $\varepsilon = 1\%$ between two iterations.

The methodology is applied to a simplified European network of 123 European cities and 256 edges, using the network and demand data of Grolle et al. (2024). A total of 5 scenarios are tested: In the baseline scenario, eleven national operators, each required to keep an initial network within its region, and three private operators which are not bound to their initial lines,

all attempting to maximise profits, compete on the network. Additional experiments vary the transfer penalty between set operators (0 and 60 minutes), which represents higher and lower levels of operator coordination, and replace the competing operators by a single central operator that either maximises profit or total served demand. Sensitivity analyses are performed on the line entry cost parameter, operator budgets, and removing the obligation for national operators to keep their initial network.

In the baseline scenario, operators concentrate their lines in the high-demand areas of Western Europe, where many operators run overlapping services with low individual frequencies (nearly 60% of the services run once per day and direction). These low frequencies then bundle into high-frequency corridors with many direct connections. This comes at the cost of lower-demand areas being served with only few lines and with low frequencies, and the north-east of the network remains disconnected from the rest. About 76% of the total demand is served, of which 65% without any transfer and about 91% with at most one transfer. Operators with large budgets and initial networks expand the most, and operators with small budgets lose part of their home markets to these larger competitors. The scenarios of increased and decreased operator coordination lead to only marginal changes in the network: setting the transfer penalty to 0 increases the number of services, train-kilometres and the absolute served demand (by about 2%), but lowers total operator profits by about 10%, while a higher penalty gives results close to the baseline, even being slightly better in terms of passenger performance. For the scenarios with a central operator, profit-maximisation leads to a network which has similar geographical patterns to the ones with competition, but serving slightly less demand (~72%), and a central operator maximising served demand serves 98% of the total demand with more than three times as many lines, but with lower profit.

Within the assumptions of the model, profit-maximising competition therefore leads to a high level of service in high-demand areas at the expense of low-demand areas. Taking into account the results of the multiple scenarios, this seems to be mainly caused by the profit maximisation rather than the competition itself. The best performing network from a passenger perspective is the centralised network aiming to maximise the demand served. If centralisation is not possible, which is highly likely given the large number of countries involved, increased coordination between operators can marginally improve passenger outcomes, though at the cost of operator profits. Additionally, if liberalisation of the market continues, there might be a need for EU subsidies for unprofitable lines to maintain service in low-demand regions.

This research presents some limitations and shortcomings, which can be used as recommendations for future researchers in the topic. First, TNDFSP frameworks cannot be used for actual prediction of networks and schedules due to the large number of simplifications and assumptions. The model does not include pricing or service differentiation, which are key aspects of operator competition. In terms of the implementation, a large issue is that the demand estimation for lines that are not in the network appears to overestimate demand, which contributes to the many low-frequency lines. Further, for low entry costs, this is also the cause for oscillation between network states, which leads to some scenarios never converging. The passenger assignment treats overlapping lines as independent alternatives, which not only makes it less realistic but also makes it scale poorly, leading to high running times. Finally, the budget and entry cost parameters lack realism as well, having to be added to the model for it to function rather than due to being based in reality. For future research, integrating pricing into competitive network planning, even at a smaller scale, could lead to

important insight when it comes to anticipating the future development of European rail. Simulating different types of operator behaviours (changing their objective functions or constraints) on the same network could also lead to further insight on operator competition structures. From a modelling standpoint, developing a more scalable passenger assignment considering overlapping lines, formulating a better way to assess expected demand, and improving the MILP formulation for the entry costs and budgets are all avenues that should be explored. Improving on these shortcomings could prove valuable in investigating the European rail networks in a future of open-access competition between operators.

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1 Introduction

Long-distance passenger travel has become a lot more common in the past decades. While this has positive outcomes such as increased passenger mobility and connectivity, it is linked to externalities such as pollution and contributing to climate change, as the transport sector accounted for nearly a third of greenhouse Gas emissions in the European Union in 2023 (European Environment Agency, 2026). With the goals of reducing these greenhouse gas emissions, rail transport is viewed as a more attractive and sustainable alternative (Cats, 2025). It also has high potential for improvement, as rail made up only 8.6% (511 million pkms) of all passenger-kilometres of all passenger transport in the EU27 in 2023, nearly 9 times less than cars (Figure 1.1). As such, it has been receiving increased attention from the European Union, starting with directive 91/440/EEC in 1991, which laid the foundation for future railway development on the continent. There have since been four railway liberalisation packages, the latest of which was adopted in 2016. The packages, among other things, aim to improve cross-border ticketing and booking, remove barriers of entry for new rail operators, reduce costs of authorisations and certifications, increase cooperation and interoperability between infrastructure managers to allow for more cross-border capacity, and mandate tendering for railway Public Service Operations (PSOs) (Comisión Nacional de los Mercados y la Competencia, 2026; European Commission, 2025; European Parliament, 2016). These measures are intended to open up the market for new, private competitors to challenge the current national rail providers on passenger lines, including mandatory tendering for. This has the potential to increase overall welfare by reducing the losses caused by national incumbents' monopolies, especially on long-distance lines (Broman & Eliasson, 2019).

A decade after that 2016 railway package, the long-distance passenger railway sector in Europe has progressively evolved into an increasingly competitive environment, where new operators coexist with the incumbent state operators, in countries such as Italy, the Czech Republic, Slovakia, Sweden, and Spain (Battilocchi et al., 2026). This trend is set to continue and take on larger dimensions, with operators such as Flixtrain looking to double its capacity

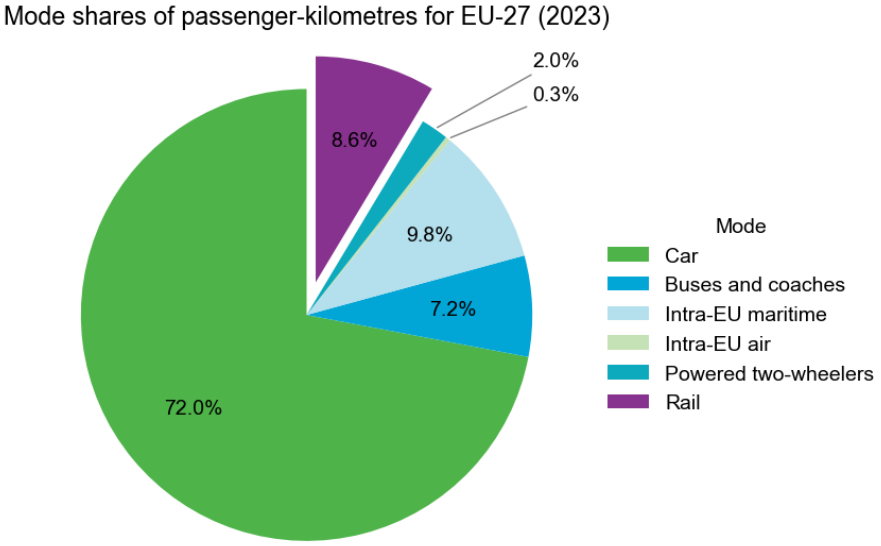


Figure 1.1: Shares of Passenger-kilometres for transport modes in the EU-27 (2023)

in 2027 in the same German market with further expansions planned for the following years (Flix, 2026) and the Italian operator Nuovo Trasporto Viaggiatori (italo) set to enter Germany starting mid-2028 (italo, 2026). Competition is also coming for Eurostar in the channel tunnel with private operators such as Virgin rail and Gemini planning an entry by 2030 (Stone, 2026) and state operators like the Italian FS, German DB and the Swiss SBB all progressing towards making connections to London a reality within the next decade (Hughes, 2023; Railway Gazette International, 2026).

A further key aspect of these European rail developments is the development of the European high-speed rail network with the Trans European transport network (TEN-T) project (European Commission, n.d.). The TEN-T plans are aimed at having a well-functioning and faster high-speed rail network across Europe by 2040, reducing travel times between major urban centres by up to half, but also improving conventional speed tracks for better speeds and higher capacities across the continent. The shift towards lower barriers to entry and fair non-discriminatory access, combined with the upgraded network, make it relevant to investigate how competition between different service providers can shape European passenger rail services.

1.1 Contribution of this study

The goal of this thesis is to find how a potential line network of European long-distance rail could look like under non-cooperative operator competition, and how that network performs in terms of operator and passenger performance indicators. The competition investigated and modelled in this research is done in terms of frequency and network-based competition, excluding both pricing and quality-based differentiation.

To investigate this, a variation of a Transit Network Design and Frequency Setting Problem (TNDFSP) is applied. This problem from the domain of Operations Research can be used to algorithmically create a line plan and their associated frequencies, as well as evaluate its passenger performance for a given transit infrastructure and passenger demand. The competition is added to this model in a game-theoretic manner, where operators each individually set their lines and frequencies responding to the lines set by competing operators, as well as the passenger demand assignment. This is done iteratively, until an equilibrium state is reached where no operator can unilaterally improve their payoff by modifying their lines and frequencies.

A case study is done on the European long-distance rail network, using the network and demand data from Grolle et al. (2024). Next to the findings about the case study itself and the potential outcomes of passenger operator competition for the European network, this also gives findings about the viability of the TNDFSP methodology in being applied to competition, its scalability to a larger network, and its shortcomings.

1.2 Research questions

Based on this problem definition, the following research question is formulated:

How does a decentralised European long-distance rail network perform given competition between service providers?

To answer this research question, a total of four sub-questions are addressed:

SQ1: What line configurations and frequencies do service providers set when competing with other providers and what network structure does this result in?

SQ2: To what extent is the passenger demand across the network serviced?

SQ3: How does the performance of the decentralised network compare to a centrally designed network in terms of the lines, frequencies, and serviced demand?

SQ4: How do different levels of inter-operator coordination impact the network outcomes?

1.3 Report outline

This report is structured as follows: Chapter 2 reviews literature of existing competition in European rail, long-distance competition modelling approaches, and TNDFSP methodology. Chapter 3 outlines the TNDFSP methodology and model framework. In chapter 4 the case study of the European network is outlined. Chapter 5 presents and analyses the results, Chapter 6 discusses the results and critically reflects on some of the shortcomings of the research. Lastly, in Chapter 7, conclusions about the findings are drawn and used to answer the research questions.

2 Literature Review

This literature review is split into four sections: In section 2.1, existing experiences of passenger rail competition in Europe are reviewed, with the goal of showing the current situation, and what the expected outcomes of competition between operators are. Then, in 2.2, existing models of operator competition in rail and air transport are reviewed, in order to find the best way to implement competition aspects into the model used here. In 2.3, TNDFSP methods are reviewed to help construct the model and finally, in 2.4 the research gap is fully outlined.

2.1 Experiences of European passenger rail competition

Operator competition in rail services generally comes in two forms (Cherbonnier et al., 2018): Competition *for* the market, where the operation of a line is awarded in advance to a single operator, which then has the exclusive rights to run on that line (Cherbonnier et al., 2018). This approach is used in countries such as the Netherlands, Sweden and Germany, especially for regional lines (Wirth & Weik, 2026), and until the post-covid reforms towards re-nationalisation, this was the most common approach to competition in the UK (Smith & Nash, 2023). The other form is competition *in* the market, or on-track competition, characterised by operators running on the same lines in an open-access market. This open-access competition is the form the European Union is trying to incentivise in order to transform the European passenger railway market, however with only limited success so far (Beria et al., 2025).

Before the fourth railway package of 2016, there existed only a few examples of actual on-track competition in the EU, namely in Italy, Austria, the Czech Republic, Slovakia, Sweden, and some failed entries in Germany. The latest package, opening domestic markets in late 2019, allowed for new opportunities for entry, most notably in the large markets of France, Germany and Spain (Beria et al., 2023). Existing case studies in those countries focus on how new, private competitors enter the market and challenge existing national providers, usually on a few lines. They then observe the consequences on aspects such as ticket prices, ridership, revenues, frequencies, service quality and welfare. Some exclusively focus on intramodal competition between the rail providers, while others also research intermodal competition, especially airlines and to a more limited extent long-distance buses.

In ex-post empirical studies, on-track competition on long-distance passenger lines has generally been found to be beneficial for customers. Frequencies on lines with competition are found to be higher in all cases examined for Austria (Tomeš et al., 2016), Italy (Antoniazzi et al., 2020; Bergantino et al., 2015; Desmaris & Croccolo, 2018), Slovakia (Kvizda & Solnička, 2019), Sweden (Vigren, 2017), and the Czech Republic (Tomeš et al., 2016), in some cases by up to 50% more daily train trips. This is due to incumbents only rarely reducing their frequencies despite the new services provided by the entrants, in order to retain their position in the market. The market shares of the entrant operators vary, with NTV and WESTBahn both hovering at around 40% of the frequencies offered for Milan – Rome and Vienna – Salzburg (Beria et al., 2025; Špetík et al., 2026). The three-way competition in Czechia had a split of around 40%/45%/15% for ČD, RegioJet and LEO Express respectively pre-covid, meaning an entrant actually had a higher market share than the incumbent (Tomeš & Jandová, 2018) . respectively Next to the benefits for customers through higher capacity and more options, the higher frequencies also lead to a more efficient usage of the existing rail infrastructure

(Antoniazzi et al., 2020). However, in some cases, such as on the Prague – Ostrava route in the Czech Republic, this has led to infrastructure reaching maximum capacity, consequently delaying regional traffic and making it difficult to slot in freight trains (Tomeš et al., 2014). Further, public service operators keeping or increasing their service on routes with competition can lead to cuts in service on other, less profitable parts of the network or times in the day (Steer Davies Gleave, 2016). Examples of this exist in Italy, where Trenitalia eliminated large numbers of Intercity services in preparation for the entry of NTV (Bergantino et al., 2015), and the Czech Republic, where ČD strengthened peak-hour service but reduced off-peak and especially nightly services as a response to the entry of RegioJet and LEO Express (Tomeš et al., 2016). In Spain, Moyano & Dobruszkes (2025) warn of a similar outcome, where ticket price cuts on the open-market HSR lines could lead to losses and issues with cross-subsidies for RENFE, who would then need to raise prices and cut frequencies on other parts of the network.

For ticket prices, findings differ more between the countries. In the short-term, entrants have commonly been setting very low prices combined with high frequencies to try to enter the market, forcing the incumbent to compete lower its prices as well. Over time, prices stabilise and, in some cases, can be found to slightly rise again. For Italy, Cascetta & Coppola (2014) do find a reduction of average HSR fares by 30% in the first year of NTV's entry. Bergantino et al. (2015) find that there is strategic pricing happening, but with the incumbent Trenitalia not strongly reducing prices. In the Czech Republic, entries from LEO Express and RegioJet caused incumbent České dráhy to aggressively slash prices, dropping by 46% within just three years (Tomeš et al., 2016). For Sweden, Vigren (2017) reports a 13% ticket price decrease within the first year of MTR entering the market. In Austria, average ticket prices fell by 20-25% within 6 years of WESTBahn's entry on the Vienna – Salzburg line. Since 2020, prices stayed stable or even slightly increased for both providers, with WESTBahn's prices now at a similar or even slightly higher level to ÖBBs (Špetík et al., 2026). The Slovak case, examined by Kvizda & Solnička (2019) is harder to use as a comparison, as RegioJet's first entry into the market was hindered by market distortion from the government strongly favouring incumbent ZSSK. Notably, they introduced free fares for students and seniors which only applied on ZSSK trains, which drove average prices down substantially but obviously cannot be attributed to competition on that route. When ZSSK reintroduced their IC services in 2017 after having removed them just the year prior, RegioJet left the market as their financial position would have become untenable. A similar experience happened to RegioJet again in Poland, where in April 2026 the operator pulled out of the Polish market after only 6 months of services on two lines, citing unfair competition by both the national operator PKP and regulator UTK (Vosman, 2026). In Slovakia, price ranges remained about 20% below pre-competition levels even after their exit. In the post-2019 opening markets of Spain and France, prices were found to have decreased by around 30% in 9 months (Brenna, 2024) and 23% in one year (Laroche, 2024) respectively. Finally, some authors suggest that competition has no significant effect on ticket prices when looking at the European market as a whole. Beria et al. (2025) find that for Italy, France and Spain, routes with competition are not found to be cheaper than monopoly routes, with prices instead being determined by subsidies and socio-economic factors due to the markets still being immature. Laroche & Lamatkhanova (2022), looking at routes in five EU countries, the UK and Switzerland find that while competition drives frequencies up, it has no significant impact on prices.

These lower prices and higher frequencies have led to significantly higher ridership across all markets (Antoniazzi et al., 2020; Cascetta & Coppola, 2014; de Rose et al., 2024; Tomeš & Jandová, 2018). Some of this ridership comes from other Intercity rail services (Desmaris & Croccolo, 2018) but also from other modes such as intercity buses, air and carpooling (Behrens & Pels, 2012; Desmaris & Croccolo, 2018; Laroche & Lamatkhanova, 2022), increasing the modal share of rail. However, despite this increase in ridership, the cheaper pricing and splitting of the demand has led to issues of financial profitability for the rail operators. Entrants like WESTBahn, RegioJet, LEO Express and italo took multiple years of operating losses before finally reaching profitability (Desmaris & Croccolo, 2018; Tomeš & Jandová, 2018), with WESTBahn for example having to reduce frequencies to survive (Ristić et al., 2022). Some private operators have also had to leave markets or even cease operations completely due to this lack of profitability, such as HKX and Locomore in Germany, who operated small network from 2012 to 2014 and 2016 to 2017 but were taken over and declared bankruptcy, respectively (Beria et al., 2025). Thus, as Álvarez-SanJaime et al. (2016) put it: “On-track competition has benefits to users in terms of fares and services, but there is a larger loss of profitability for the industry, resulting in a social welfare decrease”, and there needs to be enough growth in passenger numbers to counteract the reduction in revenue from lower ticket prices.

Rail competition is also found to impact intermodal competition, specifically with air and long-distance buses and coaches. Bergantino et al. (2015) find that airlines lowered prices by up to 30% in reaction to NTV’s entry on the Rome – Milan line. Airlines also lowered their frequencies or even fully left parts of the Italian market as a response due to their modal share strongly declining (Antoniazzi et al., 2020). Similarly, Laroche & Lamatkhanova (2022) find for seven European countries that air and HSR competing with each other decreases prices for both, while for coach and carpooling the effects are less clear.

To summarise, empirical research finds that on-track competition between passenger rail operators leads to passenger benefits such as higher frequencies and lower prices on the routes with competition. The price-cutting has a negative impact on operator profitability, which can lead to incumbent operators having to reduce frequencies on less profitable parts of the network and reduce total social welfare if the passenger numbers do not increase sufficiently. The model utilised in this thesis can investigate findings of frequencies and operator profitability, but not pricing and welfare.

2.2 Modelling of public transport operator competition

Literature using models and simulations of competition between public transport operators is of relevance to this research for two reasons: firstly, similarly to the research of existing competition presented in the previous section, it can provide insight into the outcomes of operator competition, while also allowing for the testing of different scenarios. Secondly, the methodologies used in these studies can be useful for building the model for this thesis. These models allow to test for different scenarios of competition and entries of operators into existing lines where competition does not exist yet. This can provide insights into outcomes of price setting, operator profitability, passenger distribution and other indicators in a controlled testing environment. Methodologically, this is done with game-theoretic model frameworks, attempting to find equilibria between the objectives of different actors, which are mainly the operators and the passengers.

2.2.1 Intra-Railway competition

Commonly, existing studies of competition between rail operators look at the outcomes of duopolies between a new, private entrant challenging the incumbent national provider, though some add even more operators, and others alternative modes such as air or private car which the operators must also compete with. For the rail operators, the decision variables are most commonly ticket pricing and service frequency.

Álvarez-SanJaime et al. (2015) simulate competition for a duopoly and triopoly between an incumbent, an entrant rail operator as well as an airline in the Spanish market, with both welfare- and profit-maximising functions. The model is a two-stage game, solved by finding the Nash equilibrium for the subgames, where transport operators first independently set frequencies, and then, knowing the frequencies of their competitors, set prices accordingly. They find that a welfare maximising operator disciplines the market competition in favour of passengers, as otherwise full privatisation increases prices and reduces total services. Álvarez-SanJaime et al. (2016) research the same market with a similar model but adding an infrastructure manager setting access charges in an extra stage, making this value endogenous to the model. Their results suggest that social welfare barely changes or even decreases with on-track competition, due to the loss of profits of operators outweighing the lower fares and better services for users, except if the entry generates additional passenger demand. Similar findings arise from Johnson & Nash (2012), using the PRAISE (privatised rail model) for a UK rail line, who add that reducing track access can be a solution to reestablish profitability, but this would come at the cost of higher government subsidies. The authors suggest competitive tendering as an alternative to keep financial stability and profits, but as the English example shows, this can actually lead to price increases. Ristić et al. (2022) differentiate themselves from the first two works above by using offered seat capacity and load factors as the driver of operator revenue instead of simply higher frequencies, which leads to a more realistic model. They simulate an asymmetric duopoly with differentiated products on an HSR line between an incumbent and an entrant, using a two-stage model. The offered seat capacity is first set, then the operators compete on prices. They find that a reduction of access charges increases the number of available seats on a line, arguing in favour of reducing access barriers for new operators. Highly relevant for this study is the research by Wang et al. (2022), using a multi-stage game-theoretical model split into three subproblems, where each operator sets price and frequency, then creates its schedules, before finally the passengers are assigned to the lines. The process is repeated iteratively until an equilibrium of corridor prices is reached. This is done for one HSR and three Intercity operators which for some scenarios compete or cooperate, on a network of nine corridors around Shanghai, China. Findings include that priority operators often look to cooperation to increase multi-corridor service frequency, which reduces costs for both operators and passengers, arguing for increased cooperation instead of competition. The first-mover advantage of the priority operators does however restrict the options of entrants, which can impact their profits.

Other models use the interaction between consumers choosing an operator and operators setting their prices to capture the market accordingly. Ivaldi & Vibes (2007), for example, utilise a supply and demand model where consumers choose a transport mode and an operator based on a discrete choice model to travel on the Köln – Berlin line, and operators strategically decide on prices for the services they provide. They simulate different scenarios, such as the entry of a standard rail operator, a low-cost airline, a low-cost rail operator, and the implementation of a kerosene tax. Findings include the reduction of prices of the incumbent

air and rail providers in all scenarios. Cherbonnier et al. (2018) model an oligopoly situation for both intermodal and intramodal competition between Paris and Marseille, with outcomes of competition in and for the market both considered. This model investigates short-term pricing competition, where passengers select mode and operator based on quality and prices, and operators only set prices. Findings include that opening to competition does not guarantee a decrease in prices in favour of passengers, and that the effects of opening up to competition for the market are relatively predictable and potentially positive, while those of opening up to competition in the market are uncertain.

Broman & Eliasson (2019) use a stylised two-stage simulation model where the interaction happens between rail operators and the infrastructure manager. Operators announce their desired frequencies, the infrastructure manager then sets the departure times, and finally the operators set their prices accordingly. The passengers in this model are distributed uniformly across the day. Their findings show that duopoly yields a significant increase in welfare compared to monopoly, but that operators are incentivised to monopolise.

2.2.2 Air network and frequency competition

Non-cooperative, game theoretic aspects have been used to model airline competition for longer than rail, notably due to the earlier opening to of the market to competition. Hansen (1990) applies a non-cooperative game approach using frequencies as the sole decision variable for competing airlines in the US market. Comparing the simulation to the real market, the model performs fairly well on load factors or trip length, but quite poorly on other factors, including a severe overestimation of industry profits. Many papers have since built on similar methodology, adding more stages and decision variables, such as Adler (2001) using a two-stage Nash best-response game where airlines first set their hubs and connections independently and simultaneously with an integer linear program, and in a second stage all airlines independently and simultaneously set prices for these connections. Decision variables include frequency, plane size and fares, and passengers are assigned using a multinomial logit model. Li et al. (2026) model strategic airline competition with a network and frequency planning optimisation which can capture endogenous demand-supply interactions, maximising passenger demand served. Using a game theoretic framework, it iteratively optimises the network for each airline in subsequent order until no player can unilaterally improve their performance by modifying their strategy. Other studies with similar methodology include Adler (2005), Vaze & Barnhart (2012) and Doyme et al. (2019). More in-depth literature reviews include Sun et al. (2024), who review different types of competition, which include the relevant network and frequency competition, and a section of the review of Adler et al. (2021) is dedicated solely to game-theoretic models of air competition.

2.2.3 Intermodal competition

There has also been a lot of attention dedicated to intermodal competition between airlines, high-speed rail, and intercity buses. Adler et al. (2010) use a single-stage equilibrium for profit-maximising air and rail operators, with the decision variables frequencies and fares, using a European dataset with 71 disaggregated zones. For the rail operator, the most relevant finding is that TEN-T infrastructure upgrades as well as low enough access charges are necessary for a profit-maximising high speed rail operator to enter the market. Shyr & Hung (2010), looking at a case study in Taiwan, use a single stage Nash equilibrium, optimising for profit of rail, air and bus operators with decision variables of frequency and fares. The results predict that an entry of HSR would take more than half of the passenger demand away from air and

car each. Both of these previous models utilise a Multinomial logit model for passenger assignment. Raturi & Verma (2020) utilise a three-stage game to analyse competition between air and HSR in India, where HSR first selects a speed profile, and then both actors simultaneously select fares in a second and frequencies in a third stage, all reaching sub-game Nash equilibrium. Their results suggest that the optimal HSR speeds depend on the specific market characteristics and the Value-of-Time of passengers.

Finally, Raturi et al. (2013) investigate competition between intercity buses and HSR for multiple corridors in India, with rail acting as the entrant into the market. The incumbent bus operator sets its fare and frequency strategy first, and can act like a monopolist or accommodate, before the rail operator adapts to it, and their profit functions are then iteratively maximised. In their model, the market entry of HSR depends on high demand and low sunk cost, as it otherwise struggles with profitability. For the interested reader, the review of Adler et al. (2021) also includes a section on models of intermodal competition.

To summarise, simulations and models of operator competition utilise game-theoretic frameworks to model the actions of operators, trying to find an equilibrium. This can be applied to intramodal rail and air, as well as intermodal competition. In terms of insights, they are generally similar to the findings of empirical research with lower prices, higher frequencies, and lower operator profitability.

2.3 The Transit Network Design and Frequency Setting Problem (TNDFSP) methodology

Transit Network Design and Frequency Setting Problem (TNDFSP) also termed transit network design problem (TNDP) or transit route network design problem (TRNDP) is a type of methodology used to plan and design transit networks by creating a set of lines and timetables (Guihaire & Hao, 2008). Extensive literature reviews discussing the TNDFSP methodology more in-depth include Durán-Micco & Vansteenwegen (2022a), Guihaire & Hao (2008), Kepaptsoglou & Karlaftis (2009), and Owais (2026). Additionally, Schöbel (2012) discusses basic line planning models adjacent to TNDFSP and reviews literature on relevant models, mathematical approaches, and algorithms.

These approaches most commonly take as an input a network of edges and nodes as well as a demand matrix and output a design of a network of lines and their corresponding frequencies. The goal is to optimise an objective for a transit operator, passengers, or a mix of the two. According to Owais' (2026) review of 170 papers, more than half of the studies adopt multi-objective perspectives, with the four most common objectives being minimising costs, maximising coverage, minimising in-vehicle time and minimising transfers. These objectives are optimised for by translating possible line configurations into scores that can be compared between each other (Grolle, 2020) while restricted by various kinds of constraints such as maximum number of lines, minimum load factors, and upper limits on budget and fleet size (Kepaptsoglou & Karlaftis, 2009).

Most commonly, TNDFSP problems are made up of three parts: line generation, line configuration and passenger assignment (Kepaptsoglou & Karlaftis, 2009). During the line generation procedure, a shortest-path algorithm, usually combined with a set of restrictions such as maximum path length, is used to create a pool of viable lines (Oliker & Bekhor, 2020). In the route configuration step, the lines and frequencies are set using this pool of lines and passenger demand to maximise the abovementioned objectives while working within the

constraints (Durán-Micco & Vansteenwegen, 2022a). This can be done with a wide variety of types of analytical models, mathematical programming or heuristic or metaheuristics methods, usually in iterative fashion (Kepaptsoglou & Karlaftis, 2009). Finally, the passenger assignment subproblem involves modelling the decisions passengers take to go from their origin to their destination on a given transit network. This results in loads and line usage which can be used to evaluate the performance of the lines and thus directly influences operator decisionmaking (Durán-Micco & Vansteenwegen, 2022a). It is a crucial step of the method, as even in its simplest form it is the most time-consuming part when it comes to solving the problem (Farahani et al., 2013).

TNDFSP methods are seldom used in the actual design of real transit networks, instead using real case study data to generate realistic instances or validate results (Durán-Micco & Vansteenwegen, 2022a). The vast majority of these case studies are done on urban bus networks of various sizes and less so on other modes. Notable exceptions to this for rail include Canca et al. (2019), who simultaneously determine the infrastructure as well as the line network and frequencies for Sevilla rail rapid transit for a profit-maximising approach instead of the more commonly used cost- or passenger-oriented objectives. D. Liu et al. (2020) utilise similar profit-oriented objectives and costs but without the long-term infrastructure aspects for line and frequency planning for the Chinese High-Speed railway network. Hartleb et al. (2022) apply a mixed-integer linear programming (MILP) formulation on the Dutch rail network, also optimising for profit, considering car as an alternative mode. Lestari et al. (2026) utilise an iterative line planning model on a small, one-corridor Indonesian HSR network, until demand converges. Finally, Grolle et al. (2024) apply a TNDFSP framework to the European HSR-network for different economic and investment scenarios, including multimodal competition with road and air.

Following Ranjbari et al. (2011), it is important to consider demand elasticity when designing transit systems as to avoid wrong estimations of usage which could consequently lead to financial losses or overuse, depending on if the demand is over- or underestimated. Examples of this in TNDFSP literature include the previously mentioned Grolle et al. (2024) and Hartleb et al. (2021) as well as others such as Albuquerque et al. (2026), Cipriani et al. (2006) and Gallo et al. (2011). They all model elasticity by adding multimodal competition coming from car, air, or other transit systems. This is applied by assuming a fixed travel time and in the case of air, fixed frequency and access/egress times which passengers consider during the demand assignment using discrete choice models. Consequently, the transit networks in these models must be fast and frequent enough to not have its demand captured by these alternative modes.

2.4 Research gap

Competition among passenger rail operators has already been well researched based on both existing examples and evidence in the European context, as well as through competition models, including for competition with alternative modes. Existing game-theoretic models are usually only applied to single lines (e.g., Álvarez-SanJaime et al., 2015; Cherbonnier et al., 2018; Ivaldi & Vibes, 2007) or small networks of a few lines (Wang et al., 2022) but are rarely scaled up to larger networks. These models also do not allow for research into network structures and regional distribution. Models of intermodal competition, specifically between air and rail, have partly been investigated at a larger scale, as Adler et al. (2010) do at the European level. However, this research is strictly centred around the intermodal competition

and does not include the actual line and frequency setting, instead simply taking total frequencies between two demand zones like for an airline.

For larger, multi-line networks, network design methodologies such as TNDFSP and similar methods have been used extensively, primarily for buses, although some case studies of rail exist (Grolle et al., 2024; Hartleb et al., 2021; D. Liu et al., 2020). To the authors' knowledge, there is no study which combines these types of line planning and frequency setting methods with competition between the operators, over a larger rail network. This research looks to fill this gap by applying a TNDFSP model, integrating operator competition through a game-theoretic, iterative framework, for a European long-distance passenger rail network. The research most comparable and relevant for this thesis is summarised in Table 2-1 below.

Table 2-1: Research gap table

Authors, year	Research focus	Relevance to this research	Difference to this research
Grolle et al. (2024)	TNDFSP for European high-speed rail network	TNDFSP framework, case study of European high-speed rail, openly available European data	Objective of minimising costs of operators, users and society; does not include competition amongst service providers; intermodal competition
D. Liu et al. (2020)	Network design problem for the Chinese High-speed rail network	Case study of a rail network, utilise a MILP for the line configuration procedure, profit-orientation	Single operator perspective; application on a small network
Hartleb et al. (2021)	TNDFSP for Dutch rail with profit-maximisation and car alternative mode	TNDFSP framework with profit-maximisation	Dutch network; no competition amongst service providers; intermodal competition
Wang et al. (2022)	Model competition-cooperation for a multi-operator rail network in China	Operator objective function, multiple profit-maximising operators on multiple corridors	Cooperation between operators; Includes scheduling problem
Adler et al. (2010)	cost-benefit analysis of infrastructure in competition between air and high-speed rail in Europe	Analyse competition between profit-maximising service providers competing for demand on a European network	Intermodal competition with air; doesn't include the frequency and line setting
Li et al. (2026)	Game-theoretic approach to competition between multiple airlines, using a network and frequency planning optimisation model	Game-theoretic and iterative framework with operators competing for demand; termination criteria; elastic demand	Air only, which means the line nature is different due to being only point to point instead of multiple stops; operators are not optimised simultaneously
Heyken Soares et al. (2019)	TNDFSP with focus on modelling and scaling down a street network	Line Generation procedure with shortest path usage maps	Single operator; small bus network
Guan et al. (2026)	Transit network design with adoption, capturing latent demand	Latent demand & Demand elasticity	Single transit agency; multimodal transit
Durán-Micco & Vansteenwegen (2022b)	TNDFSP with link capacities and crowding	TNDFSP with link capacities and a customised passenger assignment procedure, taking the k-shortest paths	Single operator; bus network; includes crowding
Borgogno et al. (2025)	Apply an Evolutionary Network Growth model to European HSR	Simulate the evolution of a European HSR network using an Iterative workflow evaluating the network based on the demand assignment	Infrastructure construction instead of line and frequency setting; network evolution over time
Cats et al. (2020)	Modelling transit network growth based on demand and cost	Simulate the evolution and growth of networks, Iterative workflow evaluating the network based on the demand assignment	Investigating the evolution of networks; no inclusion of line and frequency setting
Oliker & Bekhor (2020)	Solving a transit route network design problem for a bus network using heuristic methods	Iterative workflow of the network design problem, with a separate network configuration and passenger assignment	Single operator; small bus network

3 The TNDFSP Methodology

This chapter presents the methodology used for creating a European rail network with competing operators, utilising a modified version of the Transit Network Design and Frequency Setting Problem (TNDFSP). Section 3.1 presents the modelling assumptions that must be made to implement the model. Section 3.2 explains the graph representation of the network, then section 3.3 describes the line generation procedure of the TNDFSP. Finally, Section 3.4 goes into depth about the line configuration procedure, which is subdivided into model initiation (Section 3.4.1), passenger demand assignment (Section 3.4.2), Computation of the demand expected by operators (Section 3.4.3), description of the demand elasticity (Section 3.4.4), description of the Mixed-Integer Linear Program (Section 3.4.5), which makes up the core of the line configuration, the frequency reduction to avoid the maximum frequency constraint from being violated (Section 3.4.6), and finally the termination criteria used to end the iterative procedure (Section 3.4.7). Section 3.5 gives a brief description of the coding tools and hardware used to run the model.

3.1 Modelling and data assumptions

Due to the many different aspects as well as the scale of the model, there are a number of assumptions and simplifications for both the model, and the data used that need to be made.

- **Competition between operators only happens through differentiation of network and frequency:** Passenger fares, despite being one of the main ways of competition for open access long-distance rail (Beria et al., 2023), are not included in the variables to be optimised. The same goes for service quality and speeds, which are not differentiated between operators or lines. This means passengers strictly consider only travel times and frequencies, and operators all get a fixed amount of revenue per passenger-kilometre. Both fares and service quality are excluded due to the added modelling complexity, which places them outside of the scope of this thesis.
- **Operators decide simultaneously and independently from each other:** Operators set their lines and frequencies as a best response to the decisions of the other operators from the previous iteration, completely independently from each other. This means they do not know or anticipate the actions of the other operators on the same iteration and there is no leader or follower. The decisions are also taken with full information of the previous iterations network and passenger assignment.
- **Symmetrical Origin-Destination Matrix, rail lines, passenger paths, and edges:** The Passenger demand is assumed to be perfectly symmetrical between each origin and destination. The passenger paths are treated the same, meaning that a path from an origin to a destination is simultaneously a path from the destination to the origin. This is done due to the use of the already symmetrical data from Grolle et al. (2024) and leads to lower computational costs, as only half the OD matrix has to be used and half the paths have to be computed. Edges and lines are assumed to be perfectly symmetrical as well, so going into either direction takes the exact same travel time. This means that the optimisation is done on half the data, before the KPIs pertaining to passengers and network are doubled for the final assessment.

- **Elastic demand:** The demand is variable (elastic) and fluctuates between iterations according to the level of service, which is given by frequencies and travel times of the passenger paths.
- **No competing modes:** Only rail is modelled and there are no alternative modes. This means that if demand isn't served it is lost and marked as unserved, and demand which is denied due to saturation is also unserved and not rerouted.
- **No differentiation of demand types:** There is only one type of passenger, meaning the logit and elasticity parameters are the same for all of the demand.
- **No daytime/seasonal fluctuation of either demand or supply:** The demand and supply both do not consider time dimensions in either passenger choices or rail schedules. While this is a strong simplification of reality, this is very common for TNDFSP research due to the strong added complexity of schedule-based formulations (Durán-Micco & Vansteenwegen, 2022a). An added consequence of this is the assumption that all passenger trips can be done within a day and that the rail schedule is coordinated perfectly to allow for relatively consistent transfer times, both of which are very strong assumptions especially for long-distance rail. Disruptions are also not considered.
- **Homogeneous train fleet and interoperable network:** The train fleet is homogeneous in terms of capacity and maximum speed and assumed to be able to run on the whole European network. Further, the fleet of each operator is not limited, and the purchase and maintenance of the fleet is included in the line entry and operation costs.
- **Simplified station structures and identical stopping times:** Dwell times are assumed to be the same at each station and there is also no station capacity. The physical restrictions of stations are ignored when building lines and dwell time are assumed consistent across all stations. This includes stations where trains would require turning around such as terminal stations and is an especially strong simplification when considering cities with multiple (terminal) stations such as London or Paris, which are assumed to be able to facilitate through traffic in this model.

3.2 Network representation

The network is expressed as an undirected graph $G = (N, E)$ where the set of nodes $N = \{n_1, n_2 \dots n_{|N|}\}$ represents the cities and the set of edges $E = \{e_1, e_2 \dots e_{|E|}\}$ represents the rail infrastructure connecting those cities. On this graph, the set of rail lines $L = \{l_1, l_2 \dots l_{|L|}\}$ is made up of lines that represent sequences of directly connected nodes via their connecting edges $l = \{e_x, e_y \dots e_z\}$. Since multiple operators can operate the exact same line l, the line representation is extended to $L(S)$ for each operator $s \in \boldsymbol{S}$ which operates on a given line. To clearly differentiate these extended "operator-lines" from the lines L in writing, they are termed *services*. A small example network highlighting the difference is shown in Figure 3.1, where the left side represents a line $l_1 \in \boldsymbol{L}$ going through nodes $\{1, 2, 3\}$, and the right side represents a situation where operators $\boldsymbol{A}$ and $\boldsymbol{B}$ operate services $l_1(A)$ and $l_1(B)$ respectively on line 1.

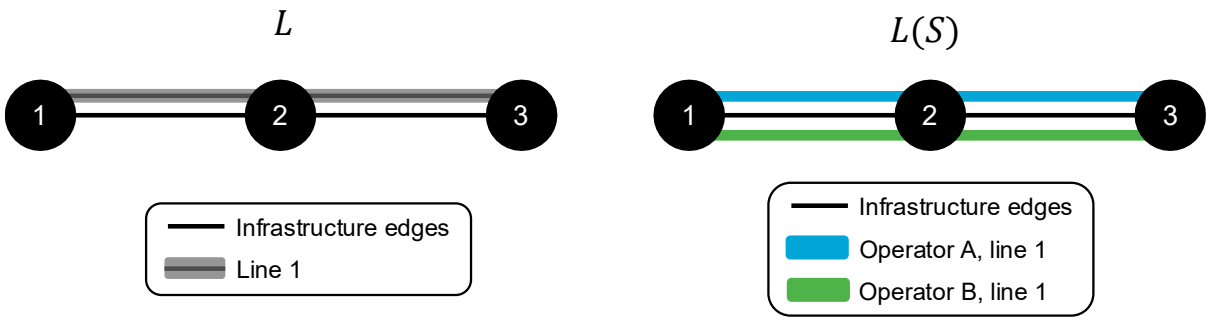


Figure 3.1: Simple example of the difference between lines and services

To represent the passenger paths for the demand, considering both the lines and the operators, the Graph is extended to $\tilde{G} = (\tilde{N}(L,S), \tilde{E}(L,S))$ based on Heyken Soares (2020). Nodes used in multiple services are duplicated, and an additional transfer edge is added, with weight $t^{tr} = \beta^n$ for transfers between services of the same operator, or $t^{tr} = \beta^n + \beta^{ns}$ for transfers between services of different operators. Finally, for every node N which is used as an origin and a destination by passengers, each respective extended node $\tilde{N}(L,S)$ is connected to a super-source (for origins) and super-sink (for destinations). These super-source and super-sinks are the origins and destinations of the passenger flows, and their connections to the extended nodes $\tilde{N}(L,S)$ have a travel time of 0 and a capacity of ∞ (Nussbaum, 2010). This is done in order to bundle all nodes within the extended graph back to being one origin and one destination node N, which shortens computation times for the shortest-path algorithms. An example is shown in Figure 3.2. The left shows a regular graph G with the edge infrastructure (black lines) three lines of two different operators A and B, with line 1 $\{1,3,4,5\}$, being operated by both operators and line 2 $\{2,3,4,6\}$ by operator B. On the right, the extended Graph $\tilde{G}$ is shown with nodes used in multiple active services being duplicated and with transfer links of length t^{tr}(dashed lines), which are of different values depending on whether they are transfers within the same operator or a different one. The nodes which are not on any active services (7) do not exist in the extended graph.

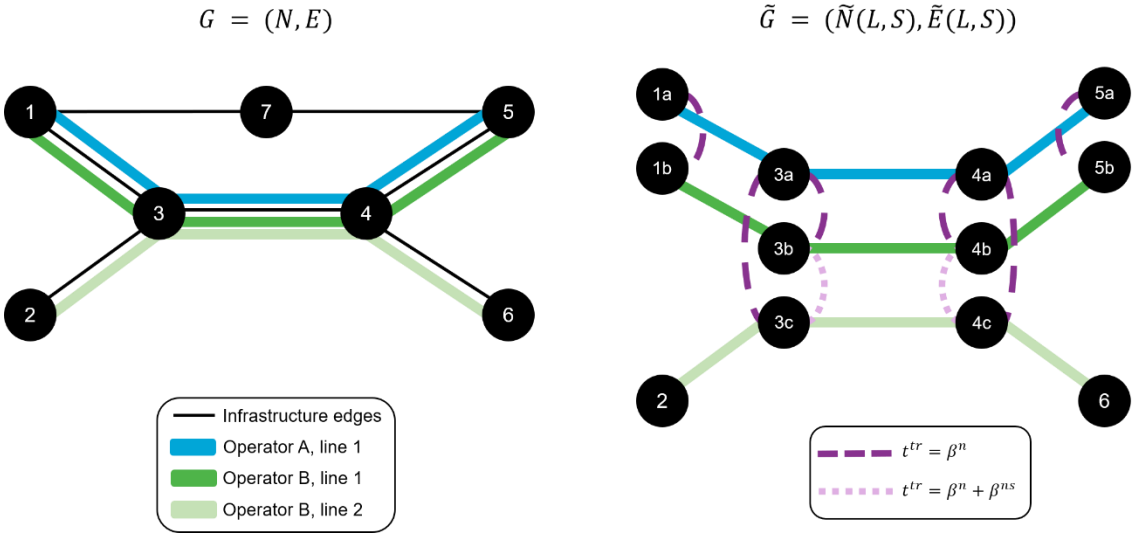


Figure 3.2: Simple example of an extended graph $\tilde{G}$

Finally, passengers travelling across the network on this extended graph to get from their origin to their destination use a set of paths $P = \{p_1, p_2 \dots p_{|P|}\}$ where each path $p = \{e_{first}, e_{second} \dots e_{last}\}$ is given by a sequence of extended edges. As was noted in Section 3.1, these paths are assumed to be symmetrical, meaning $p = \{e_{first}, e_{second} \dots e_{last}\}$ and $p' = \{e_{last} \dots e_{second}, e_{first}\}$ both take the exact same duration and capacity.

3.3 Line Generation Procedure

Based on previous works (Filgueiras et al., 2023; Grolle et al., 2024; Mahdavi Moghaddam et al., 2019) the variation of TNDFSP applied in this thesis uses a line generation procedure to create a viable pool of lines on which operators can set their frequencies on. For the line pool it is crucial to strike a balance between solution quality and size of the pool. This is especially true for a network as extensive as the one researched here. It is thus for example not a viable option due to the size of the network to take multiple or even all shortest paths between all nodes as in Fan & Machemehl (2008) or Durán-Micco & Vansteenwegen (2022b), the number of options to consider would explode. Instead, a route generation algorithm developed by Kiliç & Gök (2014), further expanded on by Heyken Soares et al. (2019) and adapted by Grolle et al. (2024) using so-called *shortest path usage maps* is utilised. The basic principle of this method is to take the shortest paths between nodes with the edge weights being a mix of

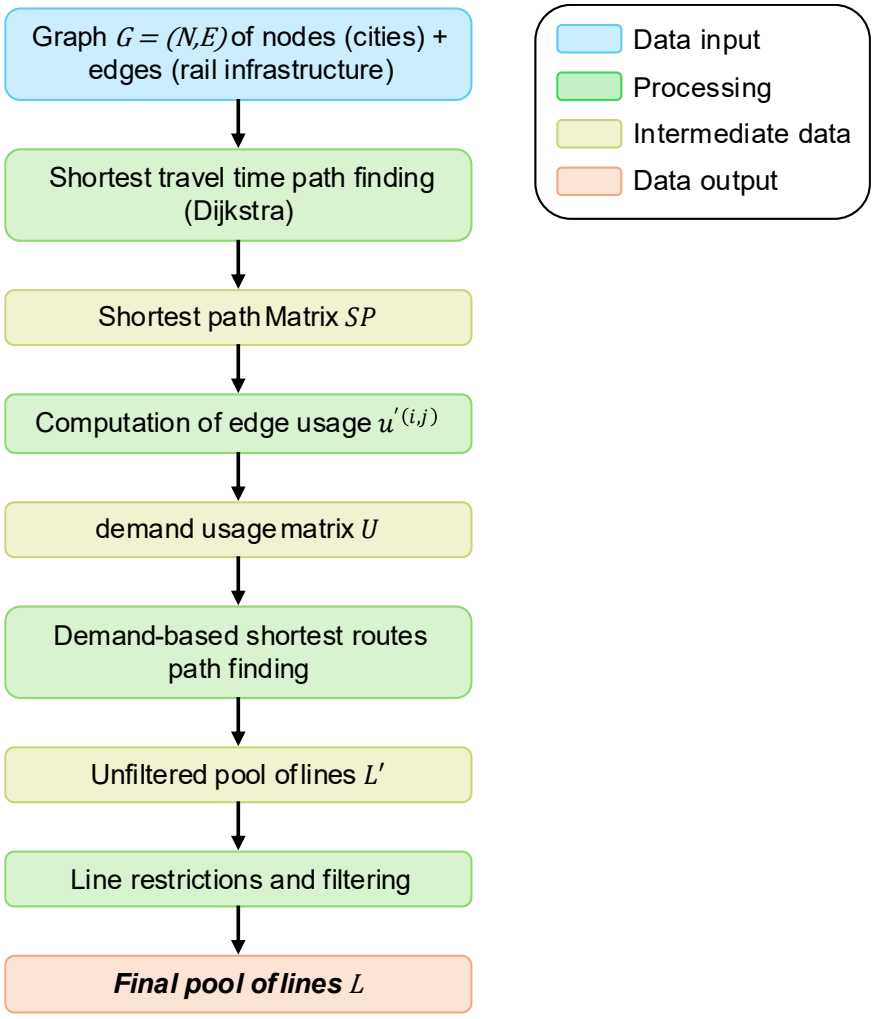


Figure 3.3: Flowchart of line generation procedure

demand and travel time. This has the benefit over conventional shortest path algorithms that edges with a high demand have a higher likelihood to be in the line pool instead of being avoided due to travel time being longer, which makes the pool be of better quality and more realistic.

The full steps of the line generation procedure are detailed below, as well as shown in Figure 3.3.

Step 1: Shortest travel time path finding

Iterating through each node $n \in N$ of graph G, the shortest path to every other node using Dijkstra's algorithm (Dijkstra, 1959) is computed, using the travel time as the edge weights. This results in a matrix of shortest paths SP between all nodes in the network.

Step 2: edge usage computation

The usage $u'(e)$ of each edge $e \in E$ in the network is computed by summing the demand $d(i,j)$ of every OD-path which uses a given edge (equation 3.1).

$$u'(e) = \sum_{\forall i,j} 1_e SP(i,j) \cdot d(i,j) \tag{3.1}$$

$where$:

$$1_e SP(x,y) = \begin{cases} 1 \; if \; e \in SP(i,j) \\ 0 \; if \; e \notin SP(i,j) \end{cases}$$

This leads to the edge usage matrix U.

Step 3: edge weight transformation

Using the variation of the method used by Heyken Soares et al. (2019), the usage $u'(e)$ is directly transformed into distances by substituting the usage from the total demand in the network

$$u(e) = \sum_{\forall i,j} d(i,j) - u'(e) \tag{3.2}$$

The resulting transformed demand usage matrix $u(e)$ thus has the lowest "distance" values for the most used edges, meaning they will be selected more by a shortest path algorithm than the edges with lower usage.

Step 4: Demand-based shortest routes path finding

Dijkstra's shortest path algorithm is used to compute the shortest paths, with $u(e)$ as the edge weight, in descending order of demand, between all the ODs in the network which have a demand greater than 10 between them. Following Heyken Soares et al. (2019), every time an edge is selected into a line, its weight is multiplied by a fixed value γ. This signifies that every time an edge is selected, its distance increases, thus making it less likely to be selected by the algorithm again. This leads to a relatively balanced line pool in which the busier links are more likely to be selected but also has some representation of the less busy links in the network, as otherwise a lot of these would find themselves completely unused. γ was arbitrarily selected as 1.05 after sensitivity tests. This results in a first broad pool of lines L'.

Step 5: Line restrictions and filtering

Taking the line pool created in the previous step, several restrictions are added to increase the quality and realism of the lines that can be selected, as well as decrease computational costs when it comes to the Line configuration procedure. The values have to be selected in a way that allows for a representative and sensible line network, without being too large to be computationally viable, while needing not to be overly restrictive as to rule out too many of the lines, but also not too broad. The selection of these filtering values is discussed in section 4.2.2.

Minimum number of stations: Each line needs to exceed a minimum threshold of stations

$$|l| \geq st^{min} \qquad \forall l \in L' \tag{3.3}$$

Maximum number of stations: Each line cannot exceed an upper threshold of stations

$$|l| \leq st^{max} \qquad \forall l \in L' \tag{3.4}$$

Maximum travel time: A line cannot exceed a certain travel time in one direction

$$TT_l^{line} \leq TT^{max} \qquad \forall l \in L' \tag{3.5}$$

Maximum infrastructural detour: the line length c_l^{line} between line terminal nodes i and j cannot exceed the shortest possible path on the infrastructure $c_{i,j}^{sp}$ by more than a detour factor det

$$c_l^{line} \leq det \cdot c_{i,j}^{sp} \qquad \forall i,j \in N, l \in L' \tag{3.6}$$

After applying these restrictions, and a few additions which are discussed in section 4.2.5.1, the output is the final line pool L. This line pool is not modified during the line configuration procedure in order to increase chances of convergence of the model.

3.4 Line Configuration procedure

The line configuration step consists of an iterative algorithm where the operators strategically set their lines and frequencies on the lines available in the line pool for each iteration. This is done using a mixed-integer linear program for each individual operator, all of which are profit-maximising. It replicates competitive interactions between operators by taking the previous iteration's line and frequency plans of competitors as an exogenous parameter in the subsequent iteration. The iteration runs until an equilibrium has been reached where no operator can unilaterally improve their payoff considering the actions of the other operators. For this research, an ϵ-equilibrium is used, which means that an equilibrium is reached if no player can increase their payoff more than ε by deviating (Nisan et al., 2007). This is not a perfect Nash equilibrium and instead relaxes the full optimisation requirement for operators, making convergence more likely. The full outline can be seen in Figure 3.4.

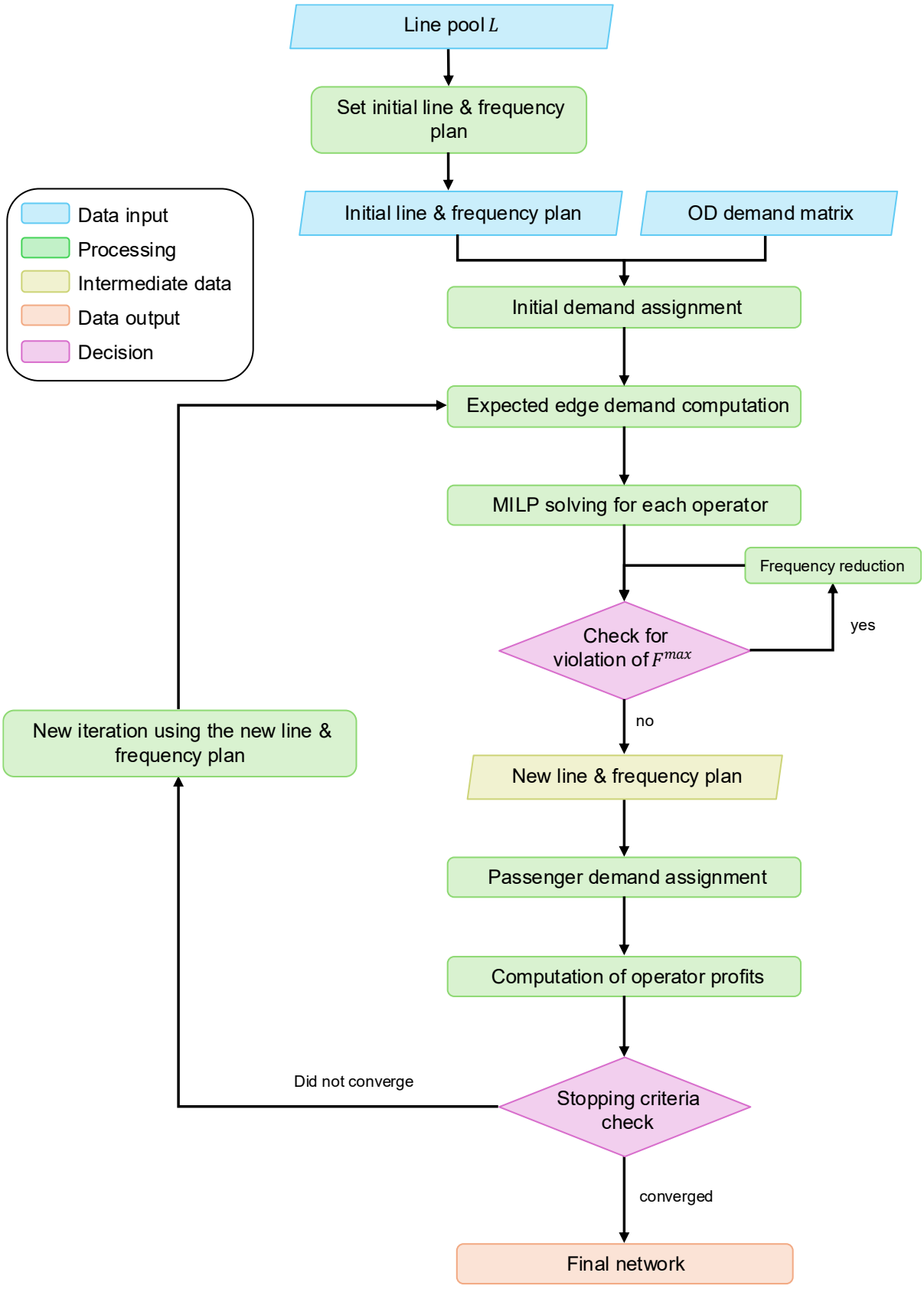


Figure 3.4: Flowchart of the iterative line and frequency process

3.4.1 Initiation

In order to initiate the network, an initial plan of lines and frequencies for each operator, a demand matrix, and the pool of lines created in Section 3.3 are all passed into the model. A more in-depth description of the OD Matrix and the initial plan are provided in Sections 4.1 and 4.2.5.

3.4.2 Demand assignment

Demand is assigned to each plan of lines and frequencies, first for the initial plan and then for each new line and frequency plan for all the subsequent iterations.

For each O-D pair, a set of attractive routes R_{ij} is first created using a k-shortest path method on the extended Graph $\tilde{G}$, between the super-sources and super-sinks. Using this method is computationally more expensive than an all-or-nothing assignment on exclusively the fastest/shortest route, but it is more realistic (Liu et al., 2010). These paths are computed using GJT (generalised journey time), following Wardman (2012) and modified to add an extra penalty for transfers that involve an operator change:

$$GJT_r = t_r^t + \beta^n \cdot n_r + \beta^{ns} \cdot ns_r \tag{3.7}$$

With in-vehicle travel time t_r^t, as well as the number of transfers n_r and number of transfers between operators ns_r and their respective penalties β^n and β^{ns}. Transfers involving an operator change are penalised more than changing to the same operator with the logic that in a competitive environment transfer from one operator to another might be less convenient, for example in terms of ticketing, or that the schedules between the trains may be less coordinated. To further limit the computation time as well as increase the realism, only paths without loops as well as within 20% of the shortest path travel time are considered (Durán-Micco & Vansteenwegen, 2022b). Additionally, the k for the shortest-path algorithm is not fixed and instead set depending on the demand between the ODs, with lower-demand ODs having lower values of k.

Then, a static passenger assignment is performed using generalised travel costs (GTC), distributing the demand flows over the network with the help of a probabilistic route choice model. The GTC, representing utility v_r for each route r between i and j is composed of the GJT and the logarithm of the service frequency, and is given as follows (Adler et al., 2010; Cats et al., 2017):

$$v_r = \beta^{GJT} \cdot GJT_r + \beta^f \cdot \ln \min_{l \in r}(f_{sl}) \tag{3.8}$$

The frequency part uses the logarithm, following the logic of Hansen (1990), who argues that additional frequencies can be expected to lead to diminishing returns in terms of gaining service attractiveness. Further, it uses the frequency of the leg of the trip with the lowest frequency, as this can be seen as the bottleneck of the entire journey (Adler et al., 2010).

The passenger demand between origin i and destination j is then distributed over all the routes r using a multinomial logit model. The probability for a passenger to take a route r is given as:

$$P_r = \frac{\exp(v_r)}{\sum_{r \in R_{ij}} \exp(v_r)} \tag{3.9}$$

This is then multiplied with the total demand for the OD to give the demand for the passengers on the different paths. The demand is finally assigned at the edge level (Cats et al. 2019):

$$d_{esl}^{total} = \sum_{i \in N} \sum_{j \in N} \sum_{r \in R_{ij}} (P_r \cdot d_{ij} \cdot z_{eslr}) \tag{3.10}$$

With the passenger demand on the OD $i, j \in N$ given as d_{ij} and z_{eslr} being 1 if edge $e \in E$ of line $l \in L$ of operator $s \in S$ is in route r.

Finally, the capacity constraint is applied to the demand by taking, for each path P_r, the highest saturation edge, given as

$$sat_{esl} = \frac{d_{esl}^{total}}{cap \cdot f_{sl}} \tag{3.11}$$

$$d_{esl}^{assigned} = \begin{cases} d_{esl}^{total} \; if \; \max(sat_{esl}) < 1 \\ \dfrac{d_{esl}^{total}}{\max(sat_{esl})} \; if \; \max(sat_{esl}) > 1 \end{cases} \qquad \forall \, \mathrm{e(l,s)} \in r, r \in R_{ij} \tag{3.12}$$

Equation 3.11 denotes the saturation for each extended edge of each operator $\tilde{e}(l, s)$. For each path r, if the saturation is less than 1, the final assigned demand $d_{esl}^{assigned}$ is given as d_{esl}^{total}. If any of the line-edges of a path r have a saturation greater than 1, $d_{esl}^{assigned}$ is given as $\frac{d_{esl}^{total}}{\max(sat_{esl})}$, reducing the demand on each line-edge to have the saturation be a maximum of 1 (equation 3.12). This is done to prevent services on the network being over capacity. The capacity constraint is strict and set to cap without considering crowding, which is done both for reducing model complexity, as well as being relatively realistic as in long-distance rail and especially high speed, it is common to have assigned seats and reservations to prevent trains going over capacity.

The final assigned demand $d_{esl}^{assigned}$ is then what is used to compute operator payoffs at the end of each iteration.

3.4.3 Expected demand

Each operator must have some type of estimation of the performance in terms of passenger demand for each line prior to selecting and setting a frequency on said line. Since each modification of the network could substantially modify the passenger assignment, doing a new passenger assignment for each possible modification of the network might seem necessary. However, as mentioned before, these passenger assignments are computationally intensive, and doing this for each possible modification for each iteration would massively increase computation times and worsen feasibility. Instead, using three steps, the expected demand for each edge of each service is approximated based on results of the previous iterations (Figure 3.5).

First, for all edges which are not in the network, a network centrality indicator is used as an estimate for the potential demand, as proposed by Luo et al. (2020) and Šfiligoj et al. (2025). One such indicator is betweenness centrality, introduced by Freeman (1977), quantifies how much a node or edge lies on the shortest path between all node pairs. It can further be adapted

to show the potential demand of the edges using the Origin–Destination-Based Betweenness Centrality suggested by Puzis et al. (2013).

$$c_B(e) = \sum_{i,j \in N} \frac{\sigma_{i,j}(e)}{\sigma_{i,j}} \cdot OD_{i,j} \tag{3.13}$$

Where $\sigma_{i,j}(e)$ represents all the shortest paths that go through edge e, $\sigma_{i,j}$ all the shortest paths and $OD_{i,j}$ the unserved demand between the nodes. $d_{esl}^{expected}$ is then set to $c_B(e)$ for every extended edge $\tilde{e}(l, s)$ on edge e.

The second step concerns extended edges $\tilde{E}(L,S)$ which are not in the network but are parallel to other extended edges $\tilde{E}(L,S)$ (same E, but have a different L, S, or both). For these line-edges, the demand assigned to the parallel line-edges in the previous iterations are averaged out to give the potential demand of the new line-edge. For lines which are not active in the network, but would add a direct connection for an OD pair (i,j) with a GJT which is better by at least 20% than the fastest connection of the previous iteration for (i,j) the following is done: The expected demand d_{esl}^{total} for all line-edges is set to be capturing the complete demand d_{ij} of all (i,j) for which the new line would lead to that 20%+ faster direct connection. Additionally, if these line-edges run parallel to another, active line-edge, that newly captured demand is added to the average demand on these line-edges as outlined in the previous paragraph.

Finally, for edges part of services already in the network, the expected demand is set as the demand assigned to the edges of these services in the previous iteration.

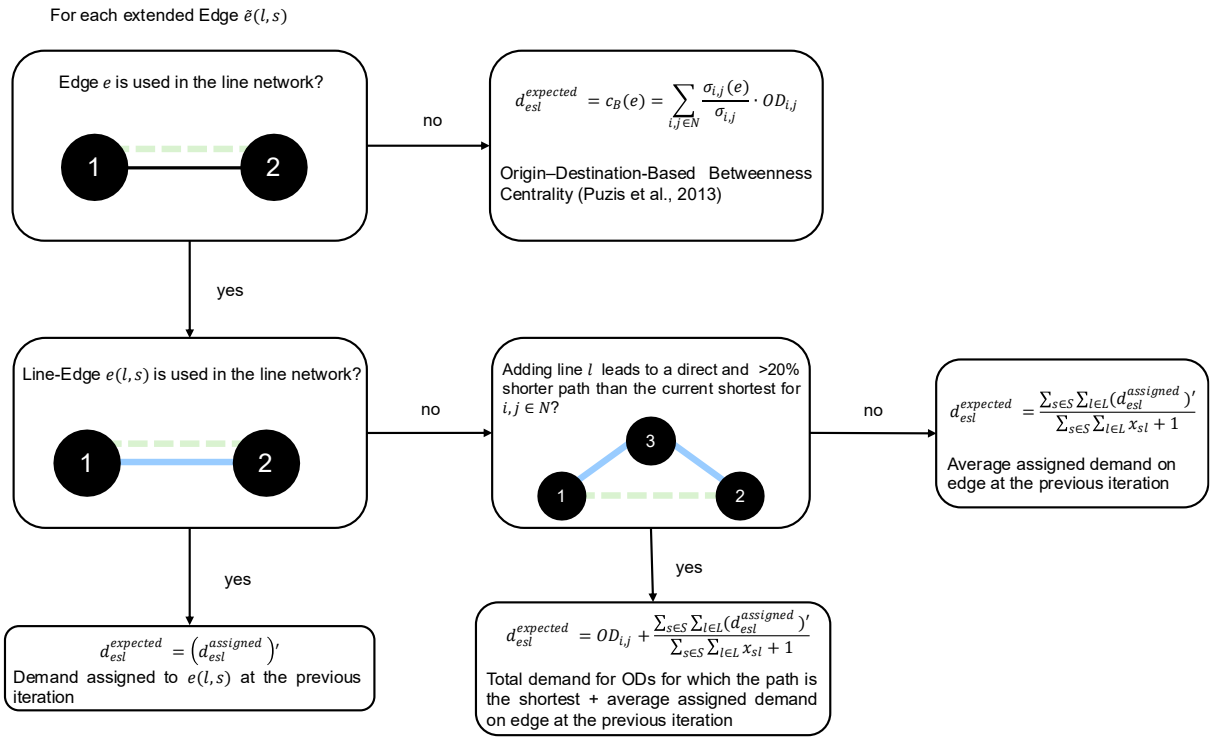


Figure 3.5: flowchart of expected demand computation

3.4.4 Demand Elasticity

As mentioned in the TNDFSP literature review in Section 2.3, demand elasticity is an important aspect of transit network design in order to correctly assess the level of demand and avoid strong over- or underestimations of network utilisation (Ranjbari et al., 2011). Unlike previous TNDFSP studies however, this thesis does not model elasticity via modal split, instead using what Farahani et al. (2013) describe as *simple elasticity,* where the demand between each origin and destination is seen as variable and does not consider any external travel modes. This is done by using elasticity parameter combined to relative changes in generalized travel costs as well as line frequency compared to a base level network performance (Lestari et al., 2026; Yap et al., 2018).

In this model, the elasticity is computed at the end of each iteration, before the new demand assignment begins. For this model, similarly to Guan et al. (2026), the demand is split into a core and a variable part, with the core representing the passengers which are guaranteed to use the rail lines if they are available and the variable part only becoming passengers if the network quality is high enough. While this is not as common of an approach as simply applying the elasticity to the whole set of demand, it is selected for this model as an OD might not be serviced at all, which would in theory signify a demand of zero, even when latent demand for rail would exist, but the elasticity would have to be set to some value even with zero frequency and theoretically infinite travel time. For the flexible part of the demand:

$$d_{ij}^{\delta} = d_{ij}^{\delta_0}\left(\varepsilon_{GJT}\left(\frac{GJT^{\delta}}{GJT^{\delta_0}}-1\right)+\varepsilon_f\left(\frac{f^{\delta}}{f^{\delta_0}}-1\right)+1\right) \tag{3.14}$$

With d_{ij}^{δ} = passenger demand between i and j for iteration δ, $d_{ij}^{\delta_0}$ = passenger demand between i and j for base scenario δ_0, GJT^{δ} = Generalised Journey Time for iteration δ, GJT^{δ_0} Generalised Journey Time for base scenario δ_0, f^{δ} = Total frequency between i and j for iteration δ, f^{δ_0} = Total frequency between i and j for base scenario δ_0, ε_{GJT} = elasticity of GJT and ε_f = elasticity of frequency (Yap et al., 2018).

3.4.5 Optimisation model

The optimisation model is the core of the line configuration procedure, where each operator $s \in S$ solves a mixed-integer linear program to maximise its profits by setting its frequencies on the available lines. This is done given the previous network state and the expected demand. Additionally, every operator's viable line pool is reduced to a subset $\boldsymbol{L_s^{viable}}$ which only includes lines which have at least one node in common with their current network. Their network must also be completely connected. This is done to reduce computation but also to avoid unrealistic networks where operators have networks spread across the entire continent, which would be operationally very difficult to execute in practice.

Table 3-1: Sets, decision variables and parameters of the optimisation model

Notation	Definition	Subsets/Units
Sets		
S	Set of operators	$s \in \boldsymbol{S}$
$S^{national}$	Subset of national operators	$s \in \boldsymbol{S}$
N	Set of nodes	$n \in \boldsymbol{N}$
E	Set of edges	$e \in \boldsymbol{E}$
L	Set of lines	$l \in \boldsymbol{L}$
$L_s^{initial}$	Initial line pool	$l \in \boldsymbol{L_s^{initial}}$
L_s^{viable}	Subset of viable lines an operator can consider	$l \in \boldsymbol{L_s^{viable}}$
Decision variables		
x_{sl}	Whether line $l \in \boldsymbol{L}$ is used (1) or not (0) by operator $s \in \boldsymbol{S}$	$[-]$
f_{sl}	Daily frequency set by operator $s \in \boldsymbol{S}$ on line $l \in \boldsymbol{L}$	$[trains/direction/day]$
$d_{esl}^{serviced}$	Demand serviced on edge $e \in \boldsymbol{E}$ of line $l \in \boldsymbol{L}$ by operator $s \in \boldsymbol{S}$	$[pax]$
z_{sl}	Auxiliary variable, becomes 1 if a line $l \in \boldsymbol{L}$ is newly used by operator $s \in \boldsymbol{S}$ and 0 if a line is either retained or removed	$[-]$
Parameters		
f_l^{prev}	Total daily frequencies per direction on line $l \in \boldsymbol{L}$ in the previous iteration of all operators $s' \in S \backslash \{s\}$	$[trains/direction/day$
x_{sl}^{prev}	Whether a line $l \in \boldsymbol{L}$ was used by operator $s \in \boldsymbol{S}$ in the previous iteration	$[-]$
k^{entry}	Entry cost to start operating a line	[€]
k^{op}	Operating costs per train-kilometre	[€]
cap	Seat capacity	$[pax/train]$
a_{el}	Binary parameter if edge $e \in \boldsymbol{E}$ is part of line $l \in \boldsymbol{L}$ (1) or not (0)	$[-]$
$d_{esl}^{expected}$	Total demand on edge e of line $l \in \boldsymbol{L}$ of operator $s \in \boldsymbol{S}$	$[pax]$
b_s	Budget of operator $s \in \boldsymbol{S}$	[€]
c_e^{edge}	Length of edge $e \in \boldsymbol{E}$	$[km]$
c_l^{line}	Length of line $l \in \boldsymbol{L}$	$[km]$
r	Revenue per passenger kilometre	$[€/pax \cdot km]$
F^{max}	Maximum allowed frequency	$[trains/direction/day$

For each operator $s \in S$:

$$\max \sum_{l \in L^{viable}} \sum_{e \in E} d_{esl}^{serviced} \cdot c_e^{edge} \cdot r - (k_l^{entry} \cdot z_{sl} + f_{sl} \cdot c_l^{line} \cdot k^{op}) \tag{3.15}$$

$$d_{esl}^{serviced} \leq f_{sl} \cdot cap \qquad \forall \, e \in E, l \in L_s^{viable} \tag{3.16}$$

$$d_{esl}^{serviced} \leq d_{esl}^{expected} \qquad \forall \, e \in E, l \in L_s^{viable} \tag{3.17}$$

$$\sum_{l \in L} a_{el} \cdot (f_{sl} + f_l^{prev}) \leq F^{max} \qquad \forall \, e \in E \tag{3.18}$$

$$\sum_{l \in L^{viable}} (k_l^{entry} \cdot z_{sl} + f_{sl} \cdot c_l^{line} \cdot k^{op}) \leq b_s \tag{3.19}$$

$$f_{sl} \leq F^{max} \cdot x_{sl} \qquad \forall \, l \in L_s^{viable} \tag{3.20}$$

$$f_{sl} \geq x_{sl} \qquad \forall \, l \in L_s^{viable} \tag{3.21}$$

$$z_{sl} \geq x_{sl} - x_{sl}^{prev} \qquad \forall \, l \in L_s^{viable} \tag{3.22}$$

$$x_{sl} \geq 0 \qquad \forall \, s \in S^{national}, l \in L_s^{initial} \tag{3.23}$$

$$z_{sl} \geq 0 \qquad \forall \, l \in L \tag{3.24}$$

$$f_{sl} \in \mathbb{Z}_{\geq 0} \qquad \forall \, l \in L \tag{3.25}$$

$$x_{sl} \in \{0,1\} \qquad \forall \, l \in L \tag{3.26}$$

$$d_{esl}^{serviced} \in \mathbb{R}_{\geq 0} \qquad \forall \, e \in E, l \in L \tag{3.27}$$

(3.15) is the objective function with the goal of maximising revenue in €/passenger-kilometres, minus costs of entry and line operation. The auxiliary variable z_{sl} is used in order to avoid deactivating a line leading to a “refund” in entry costs.

(3.16) restricts the demand serviced on any edge to be lower than the available seat capacity multiplied by the frequency, meaning trains cannot run over capacity. In (3.17) the assigned demand is further restricted to be less or equal to the expected total demand for that edge of a line. (3.18) restricts the number of trains that can be run on an edge, which represents infrastructural capacity constraints. (3.19) is the budget restriction of operators, where costs cannot be higher than the budget allocation. (3.20) simply ensures that a line $l \in L$ is selected by operator $s \in S$ if the frequency is > 0, and (3.21) conversely forces frequency to be 1 if the line is selected. (3.22) sets the auxiliary variable to be 1 if a line $l \in L$ is newly opened in an iteration and 0 if not. Constraint (3.23) enforces the initial networks of the national operators $s \in S^{national}$. Restriction (3.24) prevents there being any “refund” if a line is deselected after having been selected in the previous iteration, which should in theory help keep the networks of operators stable instead of moving across the continent, which would be unrealistic. (3.25) to (3.27) are the value constraints for the remaining decision variables.

The output of each MILP are the frequencies f_{sl} of each operator $s \in S$. These are then all merged into a new global line and frequency plan which is then used as an input for the subsequent passenger assignment.

3.4.6 Frequency reduction

Since all of the operators take their decisions simultaneously independently from each other, the constraint in equation (3.18) $\sum_{l \in L} a_{el} \cdot (f_{sl} + f_l^{prev}) \leq F^{max} \; \forall \; e \in E$ could potentially get violated, in which case the frequencies of the concerned services are reduced by one frequency at a time starting at the highest frequency service, until the constraint isn't violated anymore. This is done as it is the easiest way to reduce the frequencies, and any rule to reduce it for all operators or all lines on that edge proportionally could run into issues if an operator exclusively operates services with frequencies of 1 on that edge.

3.4.7 Termination criteria

There are three termination criteria in this model: one is reaching the maximum number of iterations of 50, indicating no equilibrium could be reached. This would indicate that no network state could be found where operators are not unilaterally incentivised to change their line and frequency network, likely caused by an unstable model leading to wrong demand expectations. The second termination criterion is reaching an ε-equilibrium, where the objective functions of each rail operator change by less than the convergence threshold of $\varepsilon = 1\%$ between two consecutive iterations (Li et al., 2026). The third one is if the line and frequency network remains the same in two consecutive iterations, signifying that no operator has any reason to modify its network. The final plan can then be evaluated on network-wide KPIs, which are discussed in Section 4.4.

3.5 Model implementation

The model is written using Python 3.13.12 using Visual Studio Code 1.134.0. For the graphs and shortest path models, the NetworkX library is used, and the solver is Gurobi 13.0.1. Everything was run on a personal laptop with an Intel ® processor, Core™ i7-13620H, 2.40 GHz with 16 GB of RAM.

4 Case study of the European long-distance rail Network

This chapter presents the data as well as the specified parameters and key performance indicators (KPIs) for the case study the methodology is applied to. Section 4.1 presents the dataset of the European rail network. In 4.2, the specific parameter values used for the baseline scenario in terms of network, LP, demand assignment, as well as the initial model state, with the levels based on previous research, are presented. Section 4.3 shows the additional experiments and sensitivity analyses which are to be conducted in addition to the baseline scenario. Finally, Section 4.4 presents the KPIs the network is going to be evaluated on.

4.1 Data and preprocessing

The data for this research is taken from Grolle et al. (2024) who adapt it from Donners (2016), who takes larger urban areas that are connected by rail infrastructure with some additional filtering and merging to end up in a network of 124 cities serving as nodes. The edges are taken using a railway network infrastructure based on the Trans-European Transport Network (TEN-T) as proposed by the European Commission (n.d.) which results in 257 edges across Europe. Additionally, the infrastructure is assumed to all be high-speed rail, allowing speeds of up to 275 km/h.



Figure 4.1: Map of all nodes and edges in the network, with edges not selected in the pool marked in red

The demand between these cities is also taken from Grolle et al. (2024), where total demand is estimated based on air data from 2019, before the data is then split by travel mode, using long-distance travel market shares of Donners (2016). Due to how the demand is created, it assumes that rail has no demand below 100 km and above 1500 km of distance between the nodes. Applying this gives a total of 2838 non-zero Origin-Destination pairs.

Applying the Line Generation Procedure resulted in a total of 1166 lines across the network. 123 out of 124 nodes were connected, the only one missing being Ankara, Türkiye, due to its total demand being exclusively to cities outside of the 1500 km radius, thus having zero rail demand. Due to this, the node was completely removed from the network, bringing the number down to 123 nodes and 256 edges. The map can be seen in Figure 4.1. From the 256 edges, the line generation procedure did not select 12 of them to be in the line pool, which are highlighted in red on the map.

4.2 Parameter specifications

The full list of parameters used in the model can be seen in

Table 4-1: Parameter values of the model

Name	Value	Sources	Used in
t^{stop}	$4\ mins$	Grolle (2020), Janić (2016)	Line travel times
γ	1.05	Own estimation	Line generation procedure
st^{min}	$3\ stops$	Grolle (2020), Own estimation	Line generation procedure
st^{max}	$12\ stops$	Own estimation	Line generation procedure
TT^{max}	$480\ mins$	Own estimation	Line generation procedure
det	1.5	Own estimation	Line generation procedure
cap	$400\ pax$	(Praticò & Fedele, 2023), Own estimation	Optimisation model
r	$0.16\ €/pkm$	European Commission (2025), Independent Regulators' Group Rail (2024)	Optimisation model
F^{max}	$216\ trains/direction/day$	UIC (2018)	Optimisation model
k^{op}	$30\ €/train\ km$	Steer Davies Gleave (2015)	Optimisation model
k^{entry}	70 000 €	Own estimation	Optimisation model
β^{GJT}	-0.02	Chen & Souche Le Corvec (2019), Moeckel et al. (2015)	Demand assignment
β^{n}	$30\ mins$	Johnson & Nash (2012), Vrtic & Axhausen (2002)	Demand assignment
β^{ns}	$15\ mins$	Own estimation	Demand assignment
β^{f}	0.9	Adler et al. (2010)	Demand assignment
α	0.5	Own estimation	Demand elasticity
GJT^{δ_0}	$2 \cdot GJT^{SP}$	Own estimation	Demand elasticity
f^{δ_0}	18	Own estimation	Demand elasticity
ε_{GJT}	-0.85	Wardman (2012; 2022)	Demand elasticity
ε_{f}	0.15	Stoll et al. (2024), Wardman (2004)	Demand elasticity

4-1 below. The following subsections elaborate on how these values were selected.

Table 4-1: Parameter values of the model

Name	Value	Sources	Used in
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f^{δ_0}	18	Own estimation	Demand elasticity
ε_{GJT}	-0.85	Wardman (2012; 2022)	Demand elasticity
ε_{f}	0.15	Stoll et al. (2024), Wardman (2004)	Demand elasticity

4.2.1 Network values

The stop times t^{stop} at each station are assumed to be 4 minutes for every stop, which is in the range of other models (Grolle, 2020; Janić, 2016). These times are added to the travel time for each intermediate station during the line generation procedure as well as to the travel times of each intermediate station of the passenger paths.

4.2.2 Line generation values

For the line generation procedure (Section 3.3), factor γ, which updates the weights of an edge after each iteration, was arbitrarily selected to 1.05. This is close to the arbitrary value of 1.1 selected by Heyken Soares et al. (2019) also set theirs arbitrarily, but 1.05 was found to lead to a more diverse line pool.

the values for the line restrictions must be selected carefully to strike a middle ground between size and quality, restricting the pool enough to not have too many lines but not too much that the operators lack good options. The values were selected based on both Grolle (2020) and own estimations for what is the most sensible given the model.

The minimum number of stops st^{min} for each line in the pool is set to 3, in order to avoid having a pool made up of large amounts of 2 stop lines which would not majorly connect the network while enlarging the pool quite substantially.

For the upper limit, the maximum number of stops st^{max} is set to 12, which prevents lines with an excessive number of nodes especially in the denser areas of the network, as these would not be realistic for daytime long-distance rail.

The maximum line travel time TT^{max} is set to 480 mins, or 8 hours. This also prevents excessively long lines by making it so lines have to be well within the 18-hour operating days when operating in both directions and taking turnaround time into account.

Finally, the maximum detour factor det is selected as 1.5, meaning lines have to be within 1.5 times the shortest possible travel distance for each OD, to remove unrealistic and large detours.

4.2.3 LP model values

The seating capacity cap is selected to be 400 for each train. This is on the lower to medium end of modern highspeed and long-distance trains, comparing for example to Siemens' Velaro, ICE 4 (both 400-900 seats depending on the configuration (Siemens Mobility, n.d.-b, n.d.-a)) and Railjets (500 seats (ÖBB, 2024)), Alstom's Avelia Horizon (740 seats (Alstom, n.d.)) and Stadler's SMILE (405 seats (Stadler Rail, n.d.)) to cite a few. Since this is not part of the decision variables, setting a lower value means it becomes less of a blurring factor in the model (Grolle, 2020), and it also partially makes up for the assumption that, even for low frequencies, trains can capture the full daily demand if their capacity is sufficient, even though in reality the demand would likely be spread across the day[1].

Revenue per passenger kilometre r is set to €0.16, in line with findings for the European average from the European Commission (2025) and Independent Regulators' Group Rail (2024) for 2022.

The maximum edge frequency F^{max} is set as being the same for every edge $e \in E$ which is not completely realistic but is seen as an acceptable simplification due to the uncertainty regarding the data as well as the infrastructure not being the main focus of this project. UIC (2018) note a maximum capacity of 15/16 trains per hour per direction for double-tracked high-speed lines. However, this level of capacity is not realistic, and in practice find themselves lower. Additionally, parts of the infrastructure might have to be shared with other, slower trains. It is thus assumed to be 12 trains per hour, meaning F^{max} is set at $216\ trains/day$, assuming 18 hours of operation per day.

For operating costs k^{op}, Steer Davies Gleave (2015) find quite a broad spread of costs at the European level between 20 and 40 €/km, with countries in Western Europe on the higher end. This number includes both infrastructure manager and railway undertakings, net of track access charges. For this model, the value is set in the middle at $30\ €/\text{train km}$.

[1] For example, if there is a demand of 500 between two locations, a 500-capacity train could perfectly capture that demand due to the passenger assignment not using a schedule-based method. This is not as realistic in reality as the demand would be more spread throughout the day, meaning that a singular train would not capture all of that demand at once in reality.

Entry costs k^{entry} are set at € 70 000 after some sensitivity tests, which is mostly meant to avoid an overly explosive growth of the network within the first iteration as well as operators not changing between similar lines in large fashion, which increases likelihood of convergence. The parameter itself does not strictly represent anything in reality, and instead was introduced for better model computation as it limits operators' ability to capture too many lines immediately, as this was leading to issues with computation times.

4.2.4 Demand assignment values

The disutility of generalised journey time β^{GJT} is given as -0.02 per minute following similar values from Chen & Souche Le Corvec (2019) and Moeckel et al. (2015) for long-distance rail.

The transfer penalties β^{n} are given as 30 minutes, following Johnson & Nash (2012) and Vrtic & Axhausen (2002). This is on the higher end of what research finds due to the actual transfer time not being available as the model is not schedule-based and thus not incorporated into the passenger assignment.

Transfer between operators β^{ns} is set arbitrarily at 15 minutes, as no previous literature suggesting values was found. This value will be modified for two of the experiments (see section 4.3).

The Logit Frequency parameter β^{f} is set to 0.9 following results from Adler et al. (2010).

For the elasticity part, α defining the proportion between core and variable value is set to 0.5, meaning half of the demand is seen as fixed and the other half as variable.

the base GJT^{δ_0} of the journey time is set to be twice the shortest path for each OD. This is so the flexible part of the demand can both increase and decrease depending on the connections in the network based on travel times. This is far from a perfect solution but works for the modelling purposes.

The base frequency f^{δ_0} is set to 18/day, which corresponds to once per hour with the 18 hours of daily operations. This is also chosen arbitrarily for the elasticity aspects.

Demand elasticity for GJT ε_{GJT} is set to -0.85, around the values of -0.81 to -0.90 found by Wardman (2012) and Wardman (2022) for interurban trips.

Frequency elasticity ε_f is set to the relatively low value of 0.15, as found by Stoll et al. (2024). This is on the lower end due to frequency generally being less important for long-distance travel, notably as these tend to be planned more in advance meaning the convenience of high frequencies is less important than for commuting (Wardman, 2004).

Additionally, in order to reduce computational times, the values of k for the k-shortest path methods are set depending on the demand between the ODs, with lower-demand ODs having lower values of k. These were selected after a few tests and are shown in Table 4-2 below.

Table 4-2: k values used for k-shortest passenger paths

Demand between i and j	k
$OD_{i,j} < 25$	1
$25 \leq OD_{i,j} < 60$	2
$60 \leq OD_{i,j} < 100$	3

$100 \leq OD_{i,j} < 180$	4
$OD_{i,j} \geq 180$	5

4.2.5 Initial operator network values

The European rail network is split into separate zones in which a public operator is required to operate. For countries such as Germany, France or Italy, the network has sufficient nodes for operators to be specific to that country, and their line initial pools are thus based on their actual networks. Countries with fewer nodes had to be combined into one region with one operator, which means there are significantly fewer operators than in real life. These merged regions are assumed to be interoperable and be in line with the policies, even for countries outside of the EU-27. For convenience, operators for multiple countries are still going to be referred to as "national operators" as, in this model, they function in the exact same way as their single-country counterparts. The initial line networks L_s^{init} of all operators are set arbitrarily as a network made up of lines from within the pool, with all nodes in the network connected to a line. For the public operators, these initial lines are required to be serviced in every iteration going forward, meaning x_{sl} will be set to 1 for each iteration for these lines. Additionally, these initial networks of national operators must all be disconnected from each other, which is more realistic as national operators do not have obligations to run lines in foreign countries. In total, eleven zones are selected, based mostly on geographical proximity, the table of which can be seen below (Table 4-3).

Table 4-3: Initial regions and their respective countries and nodes. Cursive: extra nodes added to the respective networks

Region name	Countries and additional nodes	Number of nodes
Iberia	Spain, Portugal	8
France	France, *Geneva (CH)*	15
Benelux	Belgium, Netherlands, Luxembourg	10
Germany	Germany *(without Kiel)*, *Zürich (CH), Basel (CH)*	18
United Kingdom	England, Scotland	8
Italy	Italy	13
Poland	Poland	9
Northeastern Europe	Estonia, Latvia, Lithuania, Finland, Russia, Ukraine	10
Central Europe	Czech Republic, Slovakia, Austria, Hungary	8
Southeastern Europe	Slovenia, Croatia, Serbia, Bosnia and Herzegovina, Kosovo, Montenegro, Albania, North Macedonia, Greece, Türkiye, Romania, Bulgaria, Moldova	17
Northern Europe	Denmark, Sweden, Norway, *Kiel (DE)*	7

4.2.5.1 Line pool modifications to fit the disconnected networks

In order to have the networks of the operators be completely disconnected clusters, some further modifications had to be made to the line pool. This is due to some nodes not having any lines connecting to them which do not overlap between multiple national operators' zones. In total this concerns four cities: Groningen, Netherlands, Iași, Romania, Cluj-Napoca,

Romania, and Chișinău, Moldova. Thus, for all four of these, new lines were added to the pool in order to connect them to the correct initial network. Additionally, a line was added to connect Leipzig to Hamburg via Berlin, in order to increase the realism of the original network in Germany. This increases the total size of the line pool to 1170.

As can be seen in the table, the German city of Kiel was moved from the German to the Northern European network. This is due to the infrastructure network representation making it impossible to go from Aarhus, Denmark to anywhere else in the Northern European network without going through Kiel, as can be seen in Figure 4.2.

Figure 4.2: Infrastructure network around Kiel, Germany

The initial network map of public operators is given in Figure 4.3. Additionally, three private operators are added to the network. They are given initial lines as well but, unlike the public ones, are not required to keep them and can instead move freely around in the network looking for the highest profit line configuration. Their initial networks are centred around Prague, Milan and London respectively (see Figure 4.3 for the full map), all three of which are areas which are either already experiencing rail competition, or in the case of the channel tunnel, are expected to see a lot of competition in the near future (Battilocchi et al., 2026).

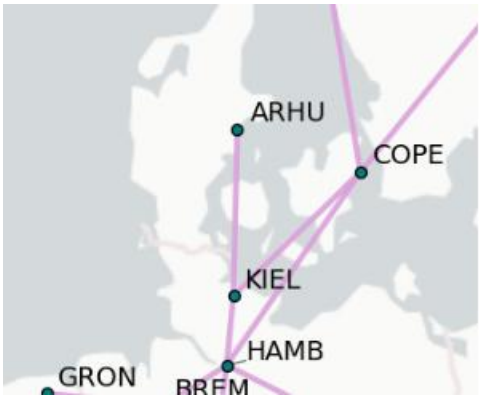




Figure 4.3: Map of the full initial network with national and private operators

4.2.5.2 Operator budgets

For the national operators, budgets were computed to be proportional to their initial network and demand on their national networks. For this, a passenger assignment excluding the private operators is computed on the initial network, assuming a frequency $f_{sl}^{initial}$ of 12 for every single line. The budget of each operator is then taken as the total costs of running the network plus the passenger revenue. This translates into needing a certain budget to cover the obligatory lines, plus additional budget from passenger revenue which can be used to expand the network.

$$b_s = \sum_{l \in L_s^{init}} \sum_{e \in E} d_{esl}^{serviced} \cdot c_e^{edge} \cdot r + f_{sl}^{initial} \cdot c_l^{line} \cdot k_l^{op} \qquad \forall\, s \in S \tag{4.1}$$

The equation is a modified version of the objective function (3.15), where budget b_s is equal to the passenger revenue plus the costs of line operation of the initial network. The thought process behind this is that each operator has an initially sufficient budget to operate a strong national network (the cost side of the equation), which can for example stem from subventions, and the passenger revenue of this initial network is added on top of that. That budget can then be spent however the operator wants to for expansion or densification of its network and remains fixed for the entirety of the line configuration process.

For the three private operators, the budget was selected arbitrarily to values around the lower-middle end of national operators. The final budgets can be seen in Table 4-4.

Table 4-4: initialisation values for all operators

Operator	National or private	region	Initial number of lines	Initial line length [km]	Initial budget [€]
A	National	Iberia	5	3 434	2 816 262
B	National	France	13	10 040	5 337 285
C	National	Benelux	5	1 337	516 115
D	National	Germany	15	7 247	4 979 925
E	National	United Kingdom	6	2 803	1 827 347
F	National	Italy	10	6 401	3 560 604
G	National	Poland	6	2 621	1 129 398
H	National	Northeastern Europe	7	6 414	2 621 476
I	National	Central Europe	4	1 781	710 744
J	National	Southeastern Europe	12	9 510	3 933 147
K	National	Northern Europe	3	2 651	2 204 967
X	Private	Prague	4	2 215	1 200 000
Y	Private	Milan	4	3 298	800 000
Z	Private	London	3	1 308	1 700 000

4.3 Additional experiments

In addition to the baseline scenario (E1) outlined above, four further experiments are investigated: E2 and E3 modify inter-operator transfer value β^{ns} to 0 and 60 respectively in order to test extreme scenarios of high operator coordination and integration, in line with the intentions of the European Commission (Directorate-General for Mobility and Transport, 2026) and high operator competition and low coordination respectively. The next experiment (E4) is done with a very large single operator aiming to maximise profits. Finally, experiment E5 also uses a singular large operator acting like a “central planner” attempting to maximise demand. For this, the objective function of that operator is modified to:

$$\max \sum_{l \in L^{viable}} \sum_{e \in E} d_{esl}^{serviced} \tag{4.2}$$

The operator budget in both experiments E4 and E5 were set to 30 000 000€ with no initial networks.

Additionally, sensitivity analyses are computed on parameters k^{entry} and the initial values of the budgets b_s, as well as testing the removal of the enforced initial network for national operators, opening up the possibility for parts of the network to not be served at all. The values of k^{entry} were set to 10 000, 25 000, 50 000, 90 000, 120 000 and 150 000 € next to the baseline value of 70 000. For the budgets b_s, the initial frequencies c, which are used to compute the budgets following equation 4.1, were set to 3, 6, 9, 15 and 18, next to the baseline value of 12.

4.4 Key performance indicators

In order to evaluate the performance of the network and answer the main research question, a selection of key performance indicators (KPIs) was selected based on transit planning literature. They are split into three categories and are shown in Table 4-5, which consider the usage of the infrastructure and the connections of the nodes in the network, passenger KPIs,

which analyse the demand patterns and paths, and finally operator KPIs, looking every operator's individual performance. Network connectivity γ is given as:

$$\gamma = \frac{|E|}{3 \cdot |V| - 6} \tag{4.3}$$

With $|E|$ = the total number of active edges in the line network, and $|V|$ = the total number of nodes in the network.

Table 4-5: selected KPIs

Network KPIs	**Unit**	**Source**
Number of active lines/services	[no. lines]	Grolle et al. (2024)
Number of used edges	[no. edges]	Grolle et al. (2024)
Number of reachable ODs	[no. city pairs]	Grolle et al. (2024)
Train-kilometres	[km]	Grolle et al. (2024)
Average stops per line/service	[no. stops]	Grolle et al. (2024)
Average line/service length	[km]	Grolle et al. (2024)
Network Connectivity γ	[-]	Derrible & Kennedy (2010)
Passenger KPIs		
Percentage of served/unserved demand	[pax] & [%]	Chakroborty (2003)
Share of served demand that can be served without any transfers	[pax] & [%]	Chakroborty (2003)
Share of served demand that can be served with 1 transfer	[pax] & [%]	Chakroborty (2003)
Share of served demand that can be served with 2+ transfers	[pax] & [%]	Chakroborty (2003)
Passenger-kms	[km]	Grolle et al. (2024)
Average travel distance per passenger	[km]	Grolle et al. (2024)
Average GJT per passenger	[min]	Chakroborty (2003)
Operator KPIs		
Profits	[€]	D. Liu et al. (2020)
Passenger-kms	[km]	Grolle et al. (2024)
Load factors	[%]	Grolle et al. (2024)
Train-kilometres	[km]	Cipriani et al. (2006)
Average stops per line	[no. stops]	Grolle et al. (2024)
Average line length	[km]	Grolle et al. (2024)

5 Results

In this chapter, the results of the TNDFSP models are presented. First, the ones of the baseline model are shown in section 5.1, with the subsections discussing the results on the KPI subgroups of network, passenger and operator KPIs, as well as their evolution throughout the iterative model separately. In Section 5.2, results of the additional experiments as well as the sensitivity analysis done on entry costs and budgets are presented, showing how the parameter tuning impacts the outcomes of the model.

5.1 Baseline model

The base model converged after a total of 15 iterations in 54 mins. The computationally most intense parts of this are: the optimisation model, taking about 20 to 60 seconds total for all 14 operators, and the passenger assignment, with about 120 to 240 second at each iteration.

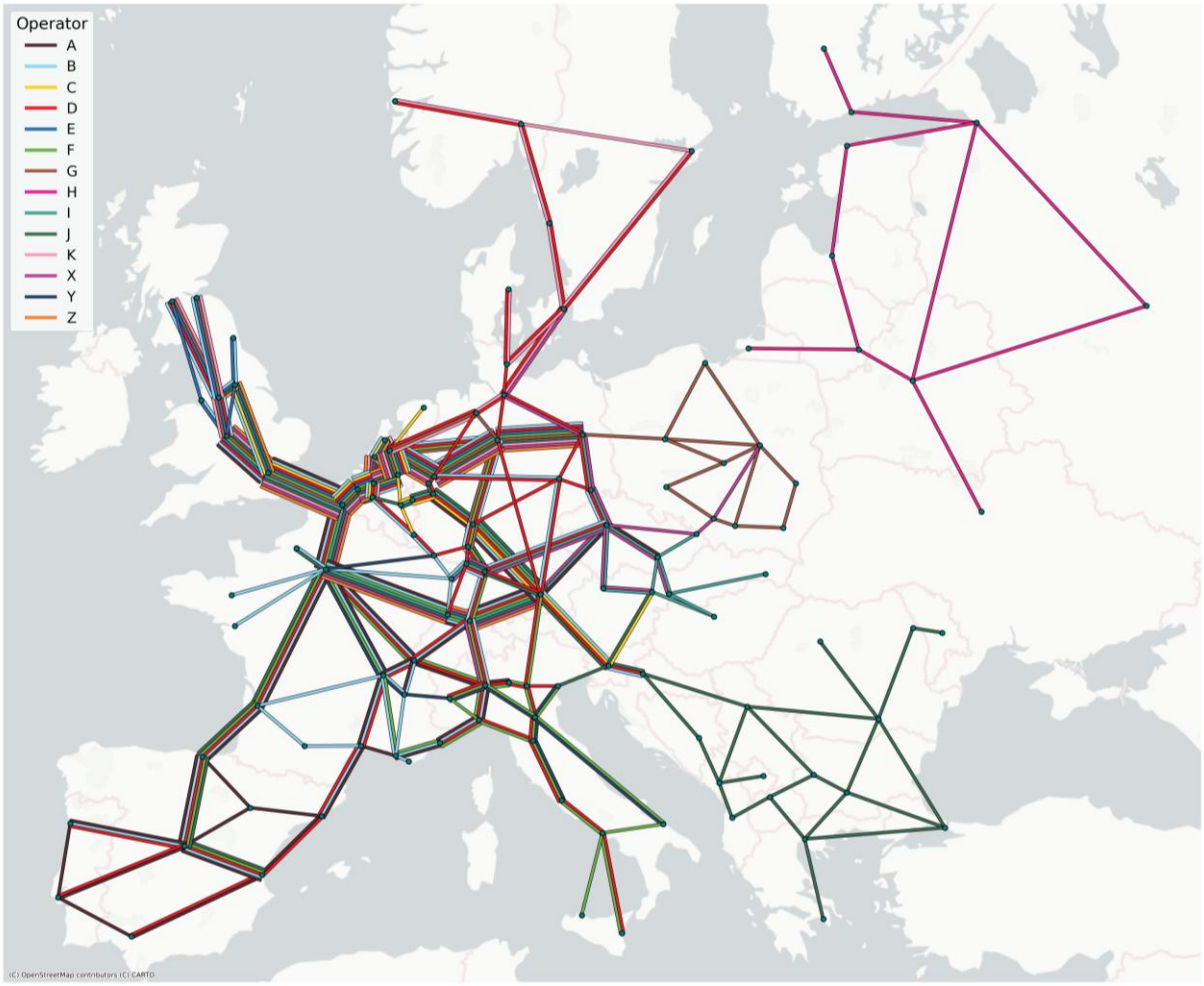


Figure 5.1 Final line network of base scenario

5.1.1 Network results

As can be seen on both the line map (Figure 5.1) and the edge frequency map (Figure 5.2), there is a strong concentration of the lines in the western part of Europe, especially connecting the UK to France, Spain, Belgium, Germany and the Netherlands. Multiple operators there operate on these edges with overlapping services, giving cities in that area a high frequency

Table 5-1: Network KPI results for the baseline scenario

Network KPIs	**Unit**	**Baseline value**
Number of active lines	[no. lines]	169
Number of active services	[no. lines]	231
Number of used edges	[no. edges]	196
Number of reachable ODs	[no. city pairs]	2 747
Train-kms	[10^3 km]	712.67
Average stops per line	[no. stops]	4.31
Average stops per service	[no. stops]	4.73
Average line length	[km]	783.79
Average service length	[km]	849.92
Network Connectivity	[-]	0.540

network with a diversity of operators. The network is not fully connected, as the Northeastern part (Russia, Baltics, Finland, Ukraine) is completely isolated, and the subnetwork of the Balkans is exclusively connected to the rest of the network through Ljubljana. The network connectivity value of 0.540 makes the network moderately dense, comparable to the results of Grolle (2020).

The network is quite extensive and well connected. In total, 196 out of the total 256 edges are used. They are all relatively far from reaching the operational maximum of 216 trains per day per direction, the highest being Lille – London with 78 (Figure 5.2), due to this being the only edge connecting London and its high demand with the rest of the European network. The



Figure 5.2 Map with total edge frequency of the baseline scenario

highest frequency nodes are London, Lille and Paris with 174, 164 and 140 total daily trains respectively.

From the 1170 possible lines in the line pool, 169 have been selected by the operators for running, for a total of 231 services. As can be seen in Table 5-2, the highest line frequency is of 12, which equals to a headway of 1h30.

The low number of frequencies but high numbers of services suggest the network is made up of diverse, overlapping lines with many operators but low frequencies from respective operators, which bundled together give corridors with high frequencies and a multitude of options for the passengers. Figure 5.3 shows the directly connected nodes for four of the highest demand nodes, where it is visible that the long-distance direct connections are good for these cities, with München having a total of 44 cities directly accessible, the most in the network. However, the network still lacks some connectivity between some major cities. Notably, Paris and Amsterdam are not connected with each other (all paths transferring in Lille), and neither are Paris and Berlin for example.

Out of all 2838 nonzero ODs, 2747 are reachable, which is due to the isolation of the northeastern part of the network. Stops per line and line lengths are similar to the average within the total line pool with under 5 stops and about 800km (). It can be noted that the service average is higher, indicating that longer lines are selected by more of the operators.

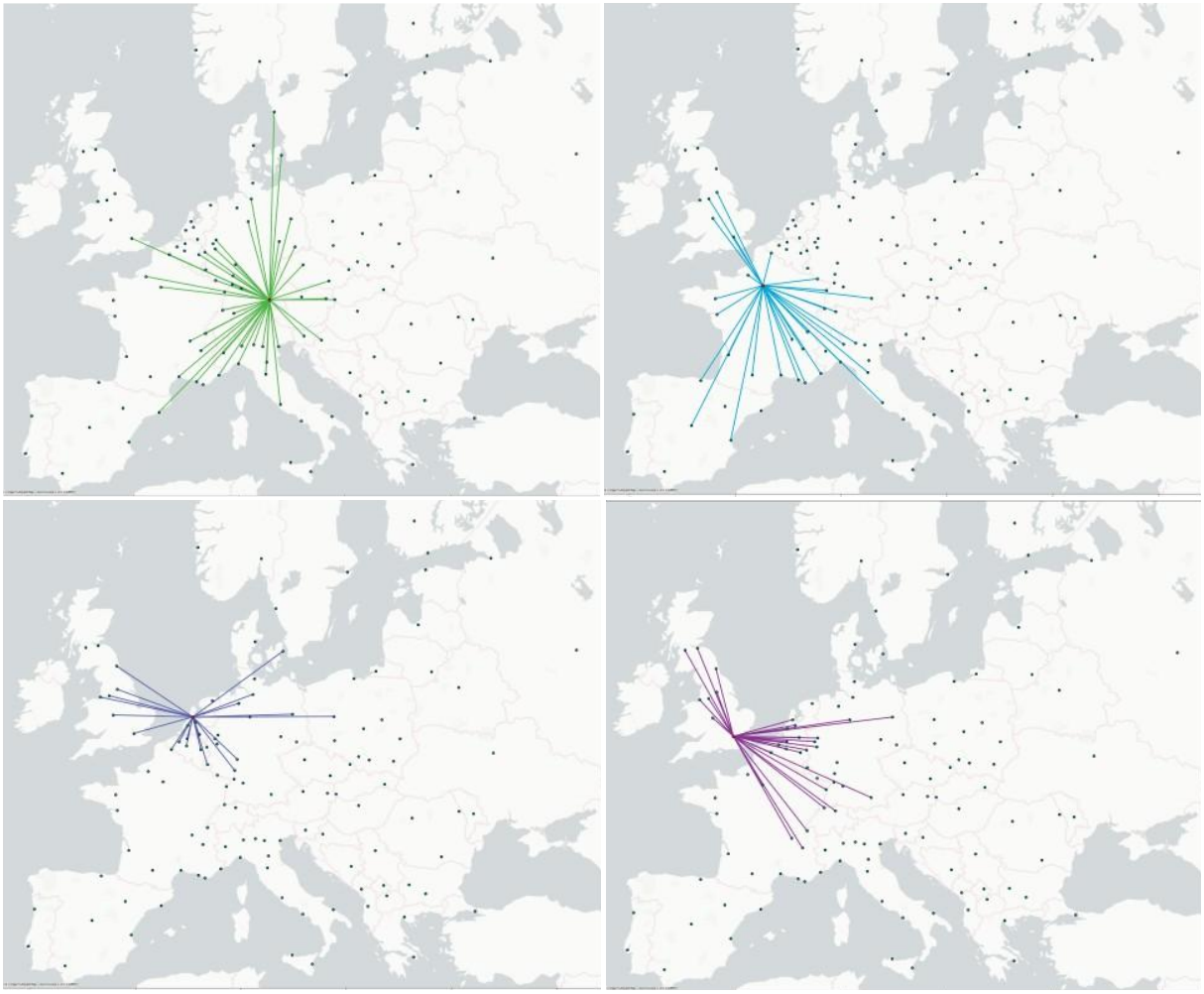


Figure 5.3: maps of directly accessible nodes for München, Paris, Amsterdam and London

Table 5-2: Lines with highest frequencies

Line	Frequency	Operators
Berlin – Hannover – Ruhrgebiet – Utrecht – Eindhoven – Antwerpen – Gent – Lille – London - Birmingham	12	9 (B, D, E, F, G, J, K, Y, Z)
Basel – Karlsruhe – Mannheim – Frankfurt – Köln – Düsseldorf	11	1 (D)
Paris – Bordeaux – Toulouse	11	1 (B)
Düsseldorf – Köln – Aachen – Liège – Brussels – Lille – London – Leeds - Manchester	9	1 (J)
Milano – Bologna – Firenze – Roma	8	2 (F, Z)
Berlin – Leipzig – München	8	1 (D)

This can be confirmed looking at the histogram of the distribution of service lengths in Figure 5.4 where the lines added to the networks of the operators (red) tend to be longer than the initial ones (blue), suggesting that longer lines can lead to higher profits compared to shorter lines, possibly due to being able to capture more of the passengers due to the directness of these longer lines.

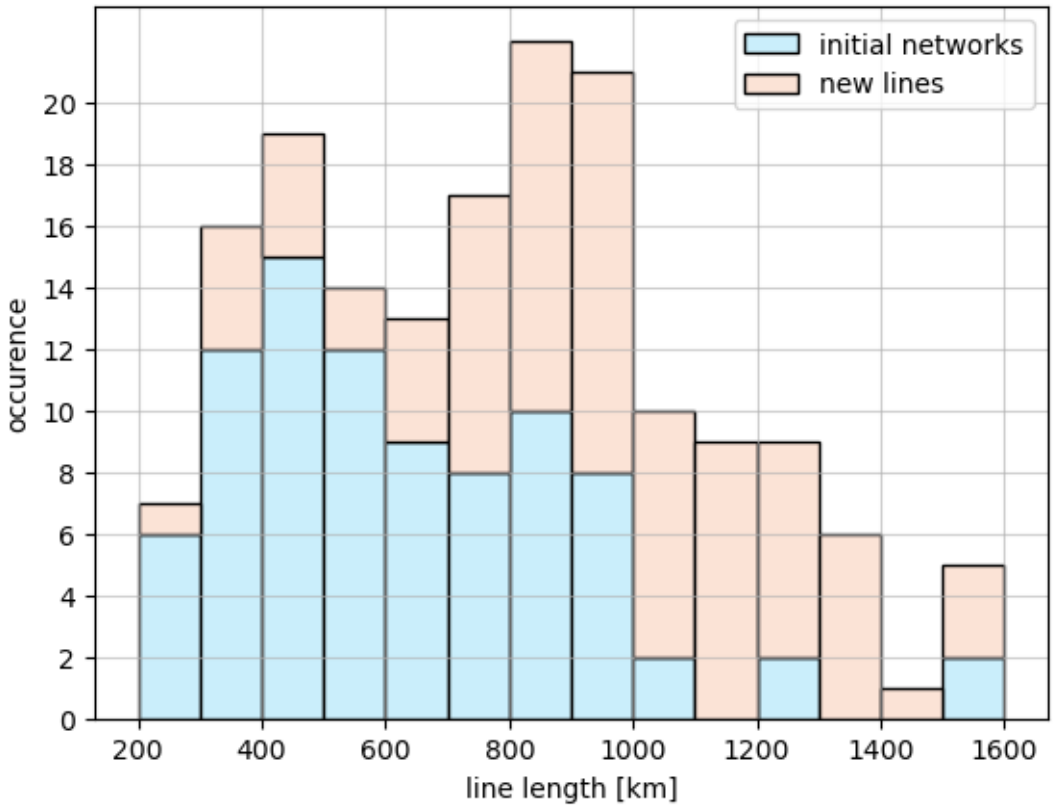


Figure 5.4: Distribution of service length

5.1.2 Passenger results

The network performance from a passenger perspective can be seen in Table 5-3, with about 76% of the total demand being serviced, 65% of that served demand being serviced directly, and almost 91% of the demand can be met with one transfer or less. The average travel distance and travel times are 617 km and 3h26, which is about the travel time from Amsterdam to Berlin with this data.

Table 5-3: Passenger KPI results for the baseline scenario

Passenger KPIs	Unit	Baseline value
Share of unserved demand	[pax] & [%]	98 599 (23.76%)
Share of served demand	[pax] & [%]	316 388 (76.24%)
Share of served demand that can be served without any transfers	[pax] & [%]	206 104 (65.14%)
Share of served demand that can be served with 1 transfer	[pax] & [%]	82 624 (26.11%)
Share of served demand that can be served with 2 transfers	[pax] & [%]	22 740 (7.19%)
Share of served demand that can be served with 3+ transfers	[pax] & [%]	4 919 (1.55%)
Passenger-kms	[10^6 km]	195.22
Average travel distance per passenger	[km]	617.03
Average travel time per passenger	[min]	205.80

Looking at how the demand is serviced at the node level (Figure 5.5), a few interesting patterns appear: Nodes on the outer parts of the network are some of the worst serviced ones, most noticeably Kyiv, Kaliningrad and Nantes, having between 10 and 20% of their demand served (Table 5-4). Kyiv and Kaliningrad can be explained by being in the disconnected network in Northeastern Europe, but geographically close to other parts of the network, meaning there is a large latent demand to these other parts. Other nodes on the outer edges like Bergen, Valencia and Oslo conversely stand out by having very high levels of demand (93-99%) served. In the case of Bergen, 90% of the node's demand is to Oslo, and of long enough distance that servicing all that demand makes financial sense in regard to passenger-kilometres. The inverse applies mostly to Oslo as well. For Valencia, this high level of service is caused by its good position between Madrid and Barcelona leading to high frequencies without highly saturated passenger paths, allowing for most of the demand to be serviced, and most of it directly. Interestingly, some of the nodes which are the best connected, such as Düsseldorf and Köln, have rather mediocre levels of served demand at around 60 to 65%, worse than other cities with similar levels of demand and service. This is caused by the way the passenger assignment treats saturation, as it reduces the demand proportionally for each OD, meaning that for nodes which are served by highly saturated lines, a lot of the demand gets reduced and thus counted as unserved.

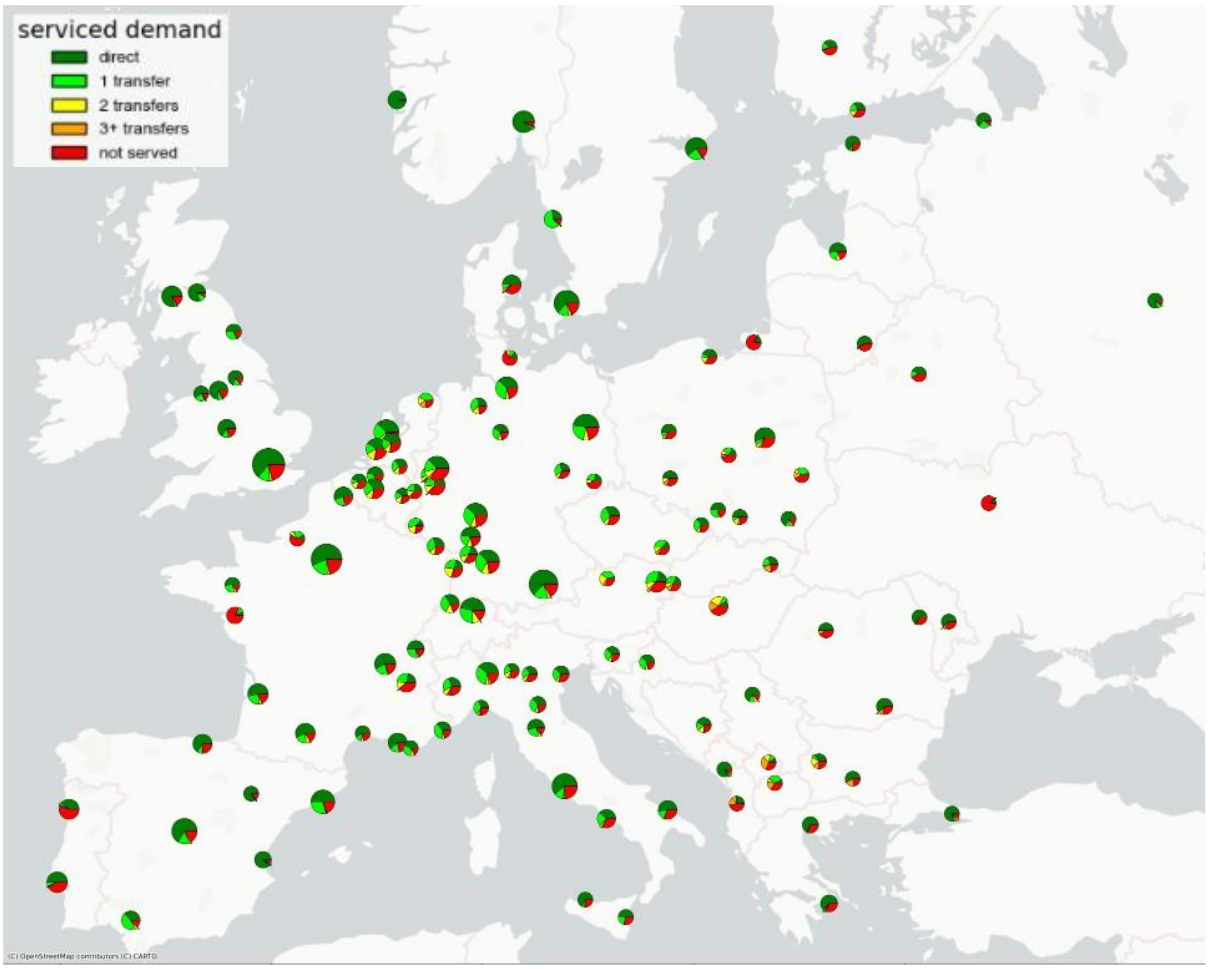


Figure 5.5: Shares of served passenger demand for each node. The size represents the total demand.

Table 5-4: Best and worst served cities in % of demand

5 Best served		**5 Worst served**	
City	***% of served demand***	***City***	***% of served demand***
Bergen	99.21%	Kyiv	10.04%
Valencia	94.01%	Kaliningrad	17.49%
Oslo	93.10%	Nantes	18.20%
Edinburgh	92.93%	Kiel	34.72%
Podgorica	91.45%	Rouen	42.68%

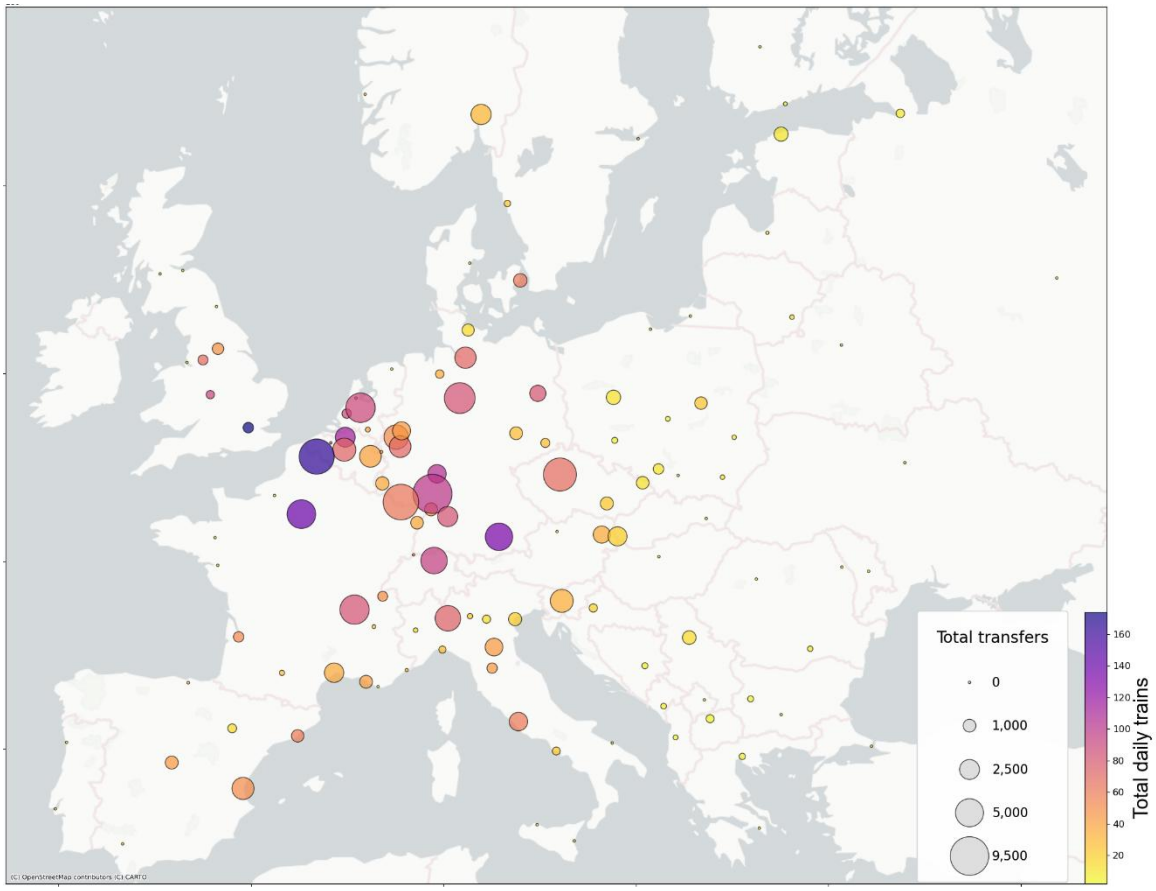


Figure 5.6: Map of transfers (circle sizes) and daily trains (colours)

Finally, looking at the stations with the most transfers (circle sizes in Figure 5.6), they are cities in Western Germany connecting the French with the German network such as Mannheim (over 9 500 transfers total) and Saarbrücken (over 8 000), as well as Lille (8 000), serving as the main transfer point to London from cities which do not have a direct connection.

5.1.3 Operator results

Looking at the operator perspective, as noted in the analysis of the network, operators gravitate towards the high-demand areas in Western Europe, even if their initial network is relatively far away (Figure 5.1, Appendix 837A). This can be seen from operator J operating lines all the way to the UK, Spain, and Northern Germany despite being the national operator for Southeastern Europe. The largest budget operators, especially B and D, unsurprisingly expand their network the most. Operator D seems to grow a lot more by expanding to more different destinations (65 total stations, more than half the nodes in the network), whereas operator B, while still going outwards, densifies its network along its main corridors (especially Marseille – Lyon – Paris – Lille – London) a lot more. Operator H in the Northeast did not expand its line network at all, likely because demand in the area is too low to justify adding more lines while remaining profitable.

The KPIs in Table 5-5 show a wide range of values for profits, passenger- and train-kms, mostly following the budget distribution. Initial network also plays a large role in profits: Operator J, despite having the third-largest budget, is not near the top of the highest profits due to its relatively long and thus expensive, but low-demand initial network in southeastern Europe. Budget also has a strong impact on the operator frequencies on edges: lower budget operators, especially C (Benelux) and E (United Kingdom) are no longer the biggest operator in their own respective regions, with especially operator B (France) having higher edge frequencies on the higher-demand parts of their initial network. For example, on the line from Antwerpen to Gent, only 2 out of the 37 trains per direction are of operator B, and the remaining 35 from other operators, of which 16 from operator C. This means a sizeable amount of the profits from these smaller national operators are partly taken away by the external competition. Due to the objective functions being the same for all operators, there are no behavioural differences between private and national operators, so any differences in results all stem from the national operators needing to keep their initial rail network.

Load factors are mostly around the 65 to 70% mark, which is in line with the usual findings in the industry (Stoll et al., 2024) and the test results from Grolle et al. (2024). Operator H in the isolated Northeastern part of the network is a strong outlier here with about 50%, owing to needing to run lines on low demand parts of the network. In terms of average line length, operators tend to prefer longer lines (as noted above and in Figure 5.4). The average length is heavily influenced by the initial network, which can be seen by operator C in Benelux having by far the shortest lines due to the relatively small but dense area it is initially operating in.

The two lines most selected by operators at 9 and 7 respectively (Table 5-5) are both relatively long at over 1300 km and connect London to higher demand cities in western Europe. The next closest drops off to 5 operators for a frequency of 5, connecting Paris to Madrid. The sharp dropoff in number suggests that across the network, while operators have some strong regional overlaps, their networks do not end up with the exact same lines but instead variations of similar ones.

Table 5-5: *Operator KPI results for baseline scenario*

operator	Profit [10^3 €]	Pkms [10^6 km]	Train-kms [10^3 km]	Load factors [%]	Nb of lines [-]	Avg stops p line [-]	Avg line length [km]	Nb of stops [-]
A	1 069.08	17.78	59.18	75.10	19	4.32	973.84	29
B	2 316.60	48.20	179.83	67.00	46	4.91	874.89	54
C	111.22	3.01	12.35	60.95	7	4.86	501.29	19
D	2 303.40	44.61	161.16	69.21	47	4.43	815.45	65
E	202.72	4.16	15.41	67.44	9	5	652.22	18
F	1 190.56	20.71	70.79	73.15	25	4.48	855.76	39
G	320.41	7.05	26.90	65.49	12	5.08	695.75	28
H	36.39	3.37	16.74	50.27	7	3.71	916.29	10
I	284.83	6.47	25.00	64.68	10	4.4	770.5	23
J	792.27	18.08	70.04	64.55	22	4.64	958.59	49
K	748.39	11.48	36.30	79.09	9	6	993.67	25
X	323.81	6.50	23.87	68.07	10	4.9	842.9	29
Y	100.17	1.80	6.29	71.77	4	4.5	785.75	11
Z	55.40	2.00	8.82	56.68	4	7.75	1 103.0	18

Table 5-6: most selected lines for baseline scenario

Line	Frequency	Operators	Line length [km]
Berlin – Hannover – Ruhrgebiet – Utrecht – Eindhoven – Antwerpen – Gent – Lille – London - Birmingham	12	9 (B, D, E, F, G, J, K, Y, Z)	1 369
London – Lille – Paris – Basel – Zürich – München	7	7 (A, B, F, I, J, X, Z)	1 345
Paris – Bordeaux - Bilbao – Madrid - Valencia	5	5 (A, B, D, F, J)	1 517

Looking into the lines themselves, it seems operators mostly select a variety of lines which are similar but differ by one or two stations and operate those lines with relatively low frequencies (1-5 per day) but end up with a high level of service due to the bundling of these lines on the corridors. In edges with a lot of competition, the frequencies are generally a reflection of the budgets of the operators, although this was not found to by systematic across the network.

The three private operators X, Y and Z all have some overlap as can be seen in Figure 5.7 , especially for operators X and Z both overlapping from Birmingham to Berlin and München but otherwise keep their initial lines active. This indicates that even when not obligated to, the operators prefer keeping their line network if the profits are sufficient, in parts also due to the

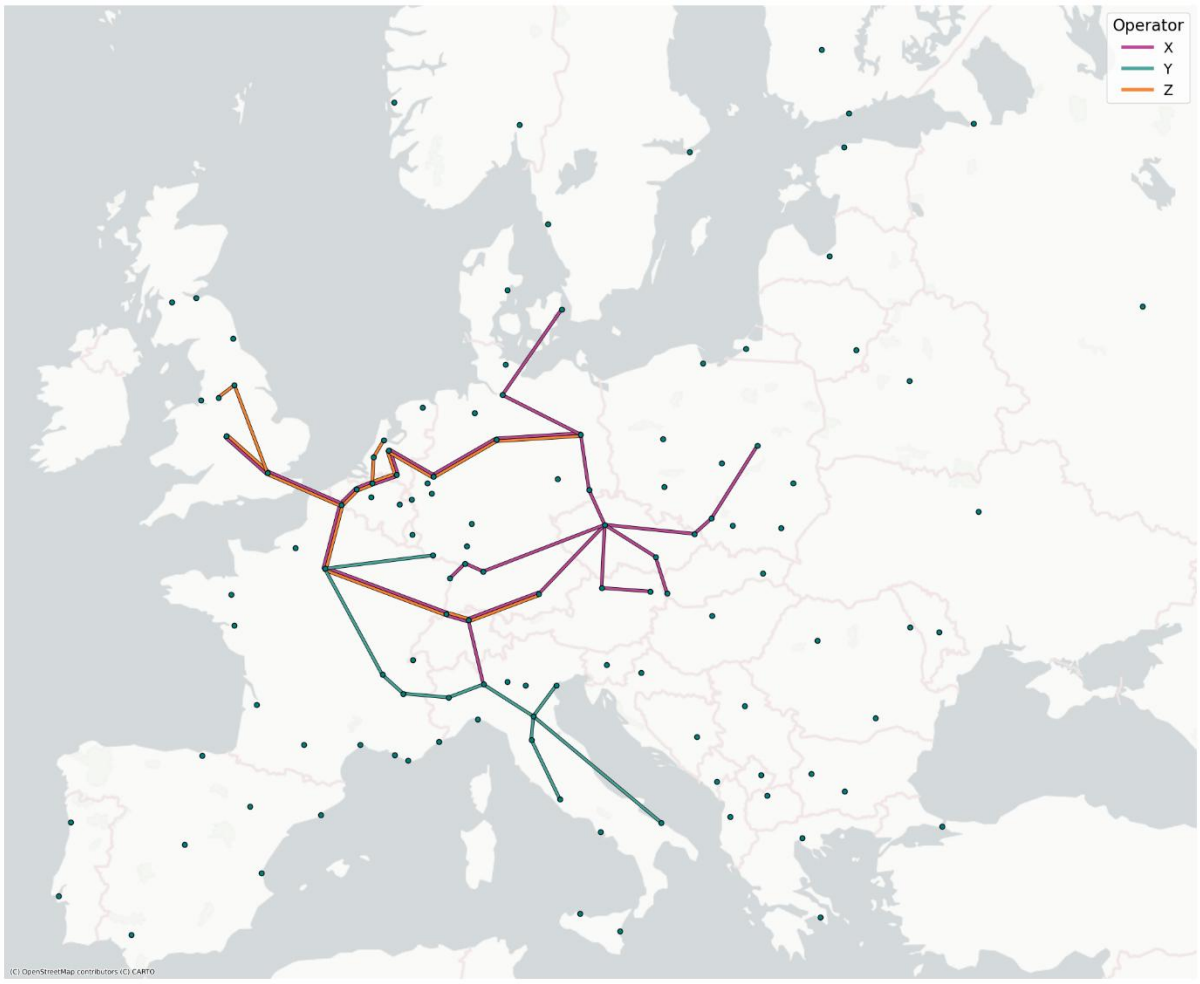


Figure 5.7: line map of private operators

higher costs to open new lines. The frequencies remain low on their networks, with notably operator Y and Z having every line on a frequency of 1 per day per direction.

These results suggest that, in this model, the optimal behaviour for profit-maximisation for these operators is to set a variety of lines with low frequency on high demand areas in an attempt to capture a maximum amount of direct demand. This is further supported by the distribution of line frequencies (Figure 5.8), which shows that nearly 60% of all operators' lines in the network are only run with a frequency of 1 per day per direction. A few high service frequencies are visible on the right of the graph with a maximum of 11 per day, as also seen in Table 5-2, three of those are operator D and one on operator B, both on lines active on high demand corridors that were already in their initial network.

While the 1 frequency per line can partly be explained by it maximising the demand as it means a high diversity of direct destinations, it is also an effect of the model. This is due to additional lines not having fixed costs associated with them other than the opening costs in the iteration where it is added to the operators' network, as well as the demand on extended edges not in the network being set to similar levels as parallel edges. This incentivises using multiple lines for the same edge.

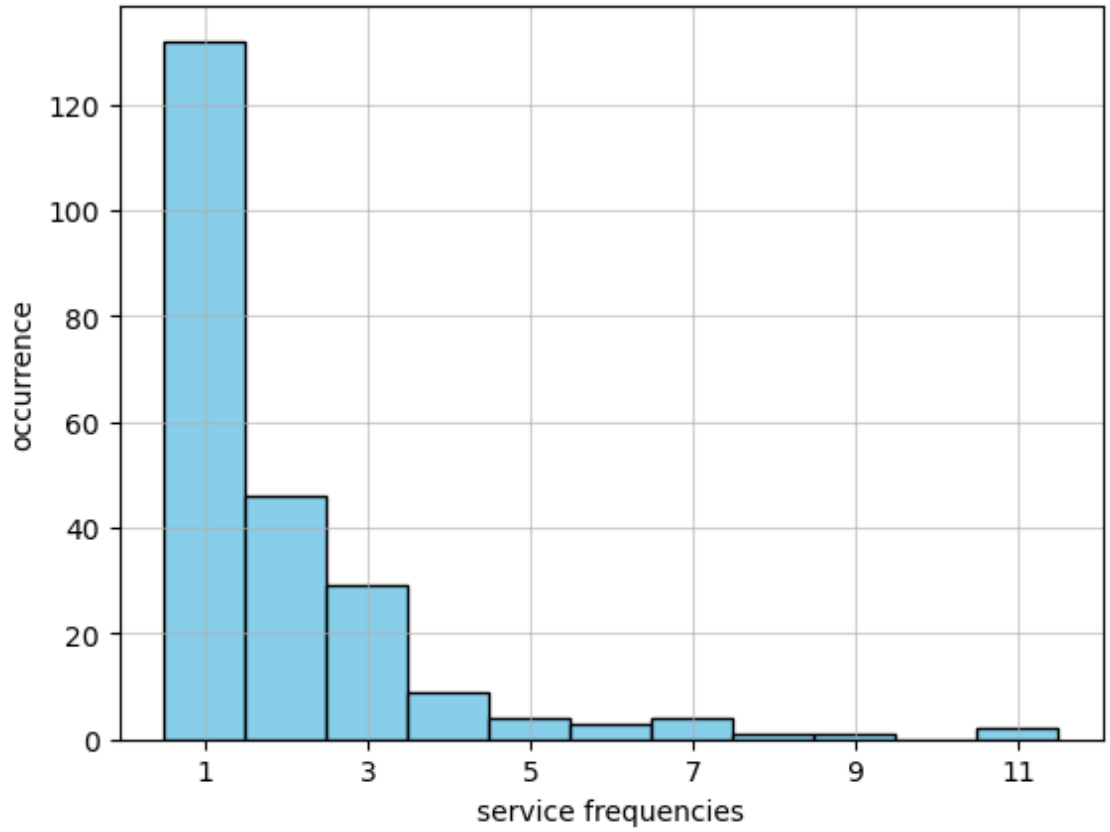


Figure 5.8: occurrences of service frequencies

5.1.4 Model Evolution

The evolution of the network and its KPIs is of interest to better understand the workings of the iterative model. As can be seen in Figure 5.9 and Figure 5.10, iteration 0 (the initial network) performs poorly due to the lack of cross-border connectivity, and some operators, especially operator J, have a very unprofitable starting network, due to the low level of demand

combined with the starting frequencies of 12 on every line and long lines. For the first few iterations there is some level of oscillation of the KPIs. In the second iteration, passengers served and the passenger-kilometres reach the peak, with ca. 4% higher values than for the final network. In the 10th iteration however, there is a very “greedy” iteration where operators have a lot more lines and serve more demand, but lose out on profits due to the high costs, which balances out on the following iterations, where it oscillates mildly before converging with no changes in networks between iterations 14 and 15. At this second iteration however, the profits of multiple operators are at relatively low values or even at the worst of the whole process. This suggests that operators try to first set high frequencies on a lot of lines with the aim of capturing parts of the market, before reducing their frequencies to get to profitability.

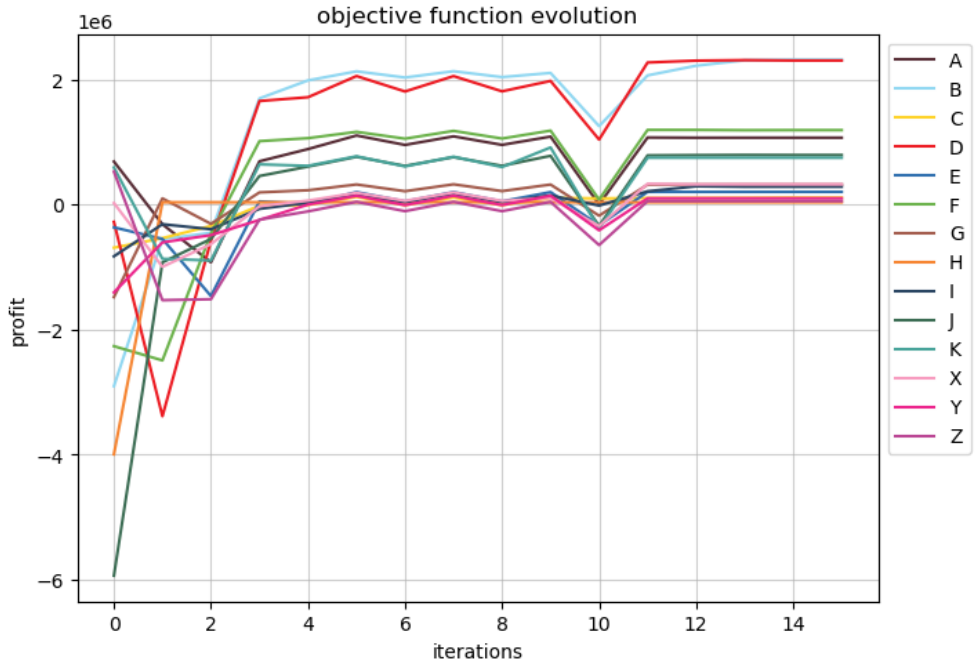


Figure 5.9: Evolution of the objective function (profits) of the operators

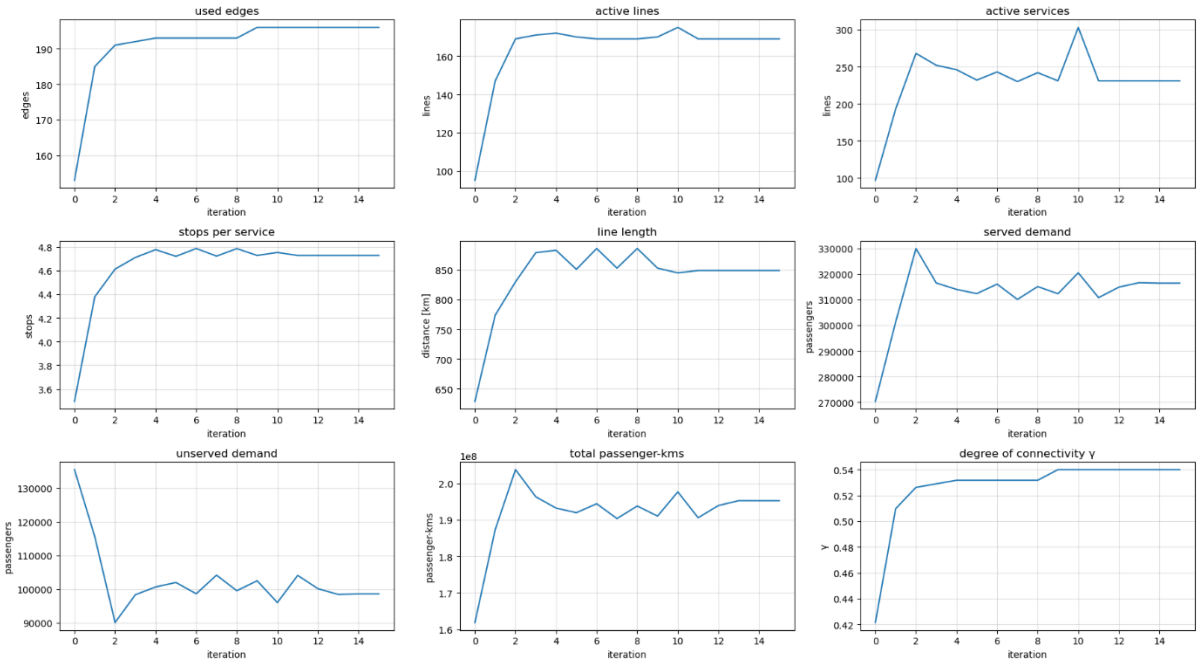


Figure 5.10: Evolution of KPIs

5.2 Additional experiments

5.2.1 Operator coordination scenarios

The two scenarios of increased operator coordination ($\beta^{ns} = 0$) and lack of coordination ($\beta^{ns} = 60$) lead to relatively similar network results as the baseline as can be seen well in Figure 5.11. The changes in cross-operator transfer penalty seem thus to only lead to minimal changes in terms of final network structure.

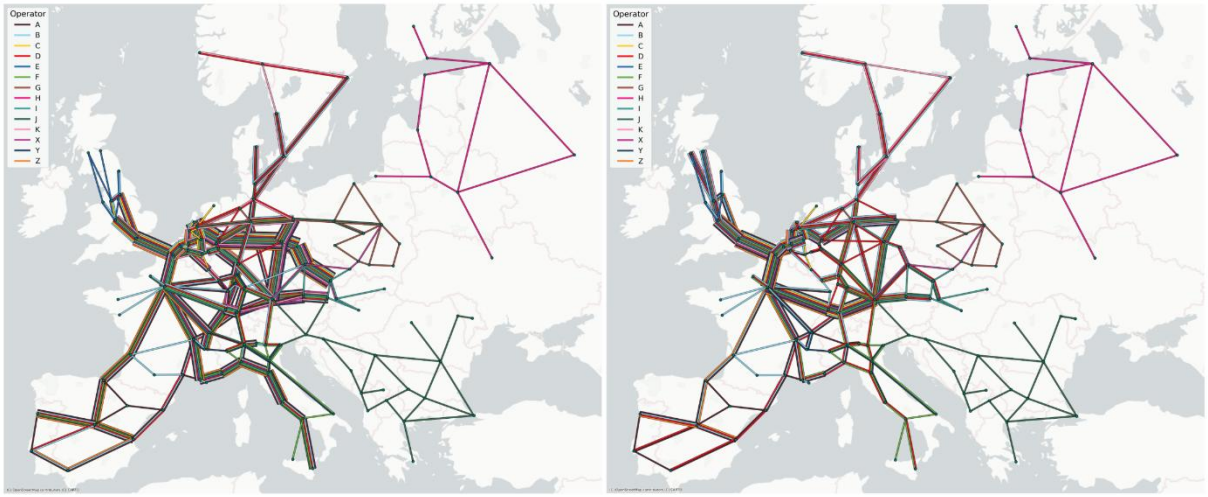


Figure 5.11: Final line network of increased coordination scenario (left) and reduced coordination scenario (right)

Some surprising findings arise from the KPIs of the different scenarios (Table 5-7, Table 5-8): while increased coordination scenario, as could be expected, leads to higher number of services (but slightly less lines), better connectivity, and more served demand and passenger-kilometres, the high cross-operator transfer penalty scenario seems to actually do comparable, if not better, than the baseline. This translates even into the passenger KPIs (Table 5-8) where the share of served demand is the highest of the three for E3, and passenger-kilometres are higher than for E1. It can be noted that the proportions of served and unserved demand are very similar between the three, but that E2 has a larger amount of total demand, caused by the newly generated demand as a response to the better levels of service. Regarding line characteristics, both the extra scenarios lead to similar lines to the baseline one, except that the services are slightly longer for the low penalty scenario E2 with 872 kms. As a consequence of those longer services, E2 has nearly 7% more train-kilometres compared to the baseline. Interestingly, these are also slightly higher for E3 than the baseline.

Table 5-7: Network KPIs of the first three scenarios

Network KPIs	**Unit**	**E1: baseline**	**E2: high coordination**	**E3: lower coordination**
Number of active lines	[no. lines]	169	163	163
Number of active services	[no. lines]	231	274	244
Number of used edges	[no. edges]	196	198	192
Number of reachable ODs	[no. city pairs]	2 747	2 747	2 747
Train-kms	[10^3 km]	712.67	760.13	722.24
Average stops per line	[no. stops]	4.31	4.40	4.35
Average stops per service	[no. stops]	4.73	4.85	4.75
Average line length	[km]	783	788	775
Average service length	[km]	849	872	857
Network Connectivity γ	[-]	0.540	0.545	0.529

Table 5-8: Passenger KPIs of the first three scenarios

Passenger KPIs	**Unit**	**E1: baseline**	**E2: high coordination**	**E3: lower coordination**
Percentage of unserved demand	[pax] & [%]	98 599 (23.76%)	106 450 (24.76%)	96 529 (23.33%)
Percentage of served demand	[pax] & [%]	316 388 (76.24%)	323 452 (75.24%)	317 282 (76.67%)
Share of served demand that can be served without any transfers	[pax] & [%]	206 104 (65.14%)	212 886 (65.82%)	206 296 (65.02%)
Share of served demand that can be served with 1 transfer	[pax] & [%]	82 624 (26.11%)	87 424 (27.03%)	80 242 (25.29%)
Share of served demand that can be served with 2 transfers	[pax] & [%]	22 740 (7.19%)	19 385 (5.99%)	23 705 (7.47%)
Share of served demand that can be served with 3+ transfers	[pax] & [%]	4 919 (1.55%)	3 756 (1.16%)	7 040 (2.22%)
Passenger-kms	[10^6 km]	195.22	197.74	196.70
Average travel distance per passenger	[km]	617.03	611.33	619.96
Average travel time per passenger	[min]	205.80	202.08	207.83

Looking at the individual operator performances (Table 5-9, Table 5-10), there is a lack of consistent patterns across the scenarios. On average, profits are higher for the scenarios with lower coordination, but that does not apply for all operators. Operators B and G follow that pattern whereas J has the opposite, performing better in the highest coordination scenario E2. the total train-kilometres are only barely higher in the coordinated scenario, and actually higher in the lower-coordination E3 than in the baseline. In combination with the lower profit this seems to indicate that operators have to expand their network more to be able to capture a sufficient amount of demand to be profitable. Operator H remains isolated in the northeast of Europe and thus sees no changes in its KPIs. The passenger paths are nearly of the exact same duration, even with the higher transfer penalty. A likely reason could be that due to the larger transfer penalty, paths with inter-operator transfers are not considered at all in the k-shortest paths, leaving only the ones within one operator. As the operators expanded all across the network, a significant number of ODs can be served by using just one operator, instead of having to transfer, meaning the increased penalty rarely came into effect.

Table 5-9: Operator KPIs for increased coordination scenario E2 (values compared to base scenario)

operator	Profit [10^3 €]	Pkms [10^6 km]	Train-kms [10^3 km]	Load factors [%]	Nb of lines [-]	Avg stops p line [-]	Avg line length [km]	Nb of stops [-]
A	1363.64	26.78	97.39	68.75	28	4.93	982.46	50
B	1937.52	42.14	160.17	65.78	46	5.04	953.96	69
C	47.45	2.26	10.49	53.94	8	5.00	489.00	20
D	1336.51	28.50	107.45	66.31	43	4.72	820.58	66
E	598.16	11.03	38.89	70.91	12	4.83	717.58	34
F	1024.94	20.32	74.22	68.45	29	4.83	866.00	52
G	136.38	4.72	20.63	57.20	14	4.50	667.86	29
H	36.39	3.37	16.74	50.27	7	3.71	916.29	10
I	123.47	4.56	20.19	56.43	9	4.78	749.89	26
J	1088.23	28.73	116.93	61.42	40	4.90	962.46	76
K	799.55	14.55	50.97	71.38	170	4.94	869.65	38
X	146.50	3.80	15.37	61.77	6	4.83	825.83	20
Y	108.11	2.87	11.71	61.30	7	4.71	757.14	23
Z	87.06	4.10	18.99	54.04	8	5.50	1084.62	34

Table 5-10: Operator KPIs for no coordination scenario E3 (values compared to base scenario)

operator	Profit [10^3 €]	Pkms [10^6 km]	Train-kms [10^3 km]	Load factors [%]	Nb of lines [-]	Avg stops p line [-]	Avg line length [km]	Nb of stops [-]
A	1340.64	24.85	87.86	70.72	23	4.61	1009.83	33
B	2491.81	49.93	183.23	68.12	49	5.1	918.12	61
C	32.17	1.48	6.8	54.27	7	4.43	454	16
D	2251.39	44.78	163.79	68.35	49	4.47	803.78	66
E	260.19	5.41	20.2	67	11	5.09	751.45	23
F	962.61	17.06	58.93	72.4	24	4.33	782.58	38
G	459.69	9.37	34.64	67.61	15	5.27	825.4	38
H	36.39	3.37	16.74	50.27	7	3.71	916.29	10
I	242.78	6.93	28.86	60.02	11	5.27	767.27	24
J	566.74	12.2	46.18	66.05	21	3.81	823.19	36
K	868.69	13.35	42.24	79.01	12	5.58	986.33	25
X	97.49	2.07	7.8	66.39	3	4.33	839.33	11
Y	102.32	2.91	12.1	60.09	6	5.83	1008	24
Z	92.07	2.99	12.88	58.04	6	5.67	1073.67	19

In conclusion, the scenarios of different levels of operator coordination indicate that an increase of coordination leads in general to an increase in service, which is beneficial to the passenger and in accordance with the EU plans. However, this on average lowers operator profits, which might lower the willingness of operators to engage in these cooperations. The differences are however rather small between the scenarios (1-3% differences in the KPIs), so these results have to be interpreted with caution.

5.2.2 Centralised single operator

Using a singular operator, profit- or demand-maximising, removes the competition for demand and the inter-operator transfers. Demand-maximisation allows for less profitable lines to still be selected and thus lower-demand areas to be serviced. As can be seen in Figure 5.13, the geographical distribution of the edge frequencies remains similar, with the London-Lille edge

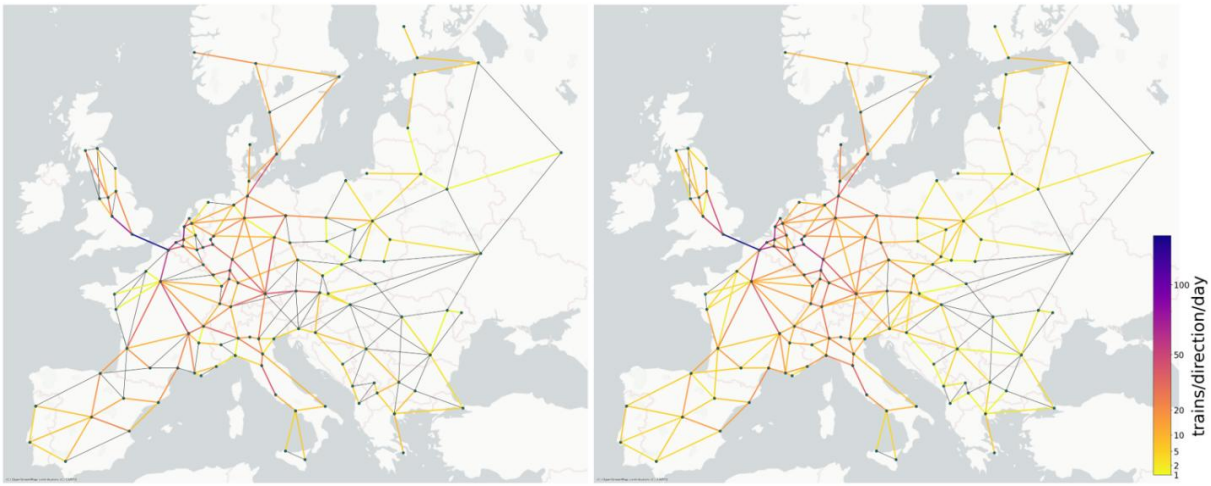


Figure 5.12: Edge frequency of centralised operator with profit-maximisation (E4, left) and demand-maximisation (E5, right)

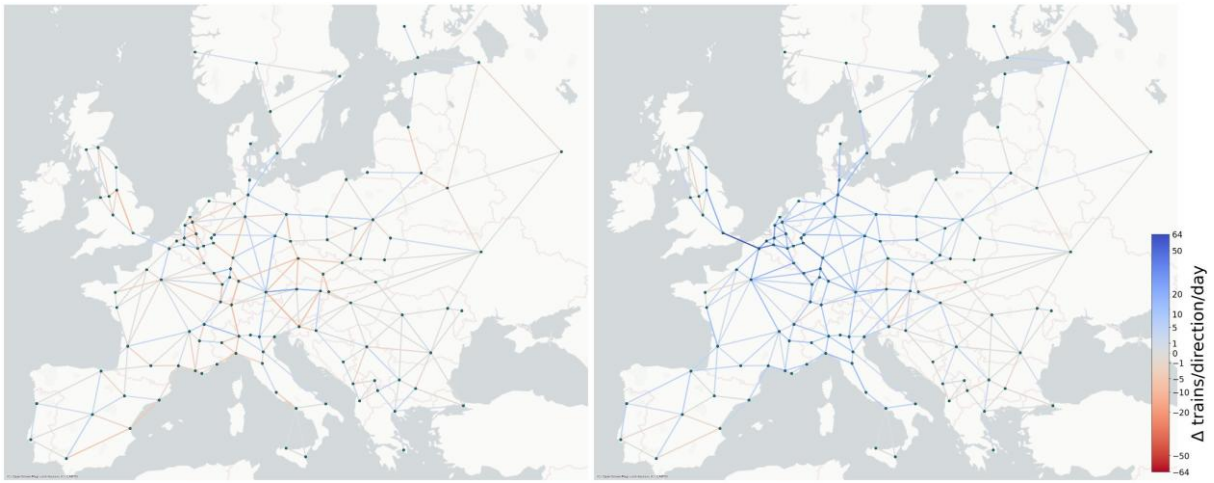


Figure 5.13: differences in edge frequency of centralised operator with profit-maximisation (E4, left) and demand-maximisation (E5, right), compared to baseline scenario

still being the most important one in the network, with frequencies of 83 for the profit-maximiser and 142 for the demand-maximiser. The differences relative to the baseline scenario (Figure 5.12) show that for the profit-maximising central planning (left) there is a slight change in distribution of which edges have higher frequencies, but without specific geographical patterns. The demand-maximising central planning (right) shows an increase on practically all edges, by as much as 64 for Lille – London.

Looking at the KPI results in Table 5-11, the number of lines is similar for the profit-maximising scenario E4, with a lower number of services. This indicates a similar level of connections for passengers, just served by the same operator. For the demand-maximising scenario E5, the number of services is more than twice as high, again with very diverse lines enabling for a lot of direct travellers, but low frequencies. These low frequencies seem to thus be the optimal outcome in each case, although this is likely also caused by the model and the way expected demand is handled. The lines are significantly longer for both centralised scenarios, which can be explained by the freedom of the operators to select any lines in the pool instead of being constrained by their initial network, as could be seen in Figure 5.8. The long lines are preferred due to the higher number of direct connections they enable, without having larger downsides

in terms of costs within the model. The profit-maximising single-operator scenario actually has a lower network connectivity, caused by the lower number of edges used in the network, indicating that that scenario leads to an even more corridor-centric network.

For the passenger KPIs (Table 5-12), the serviced and non-serviced demand levels are relatively similar between the single- and multiple-operator profit-maximising scenarios, but generally worse for the single-operator compared to the baseline. The ~2% of unserved demand in the demand-maximising scenario is caused by mismatches between the assigned demand and the expected demand in the model, still ending up with nearly 100% of the demand being serviced in this scenario. The passenger paths are still of nearly the same duration and similar distance.

For the demand-maximising scenario, as the budget is similar to the sum of all operators but leads to a more extensive network and more served demand, it seems in part to be a more effective use of money than with the operators having to fight for passengers. Part of the reason behind this higher effectiveness could be the fact that in this scenario, the operator is not forced to keep initial lines like the operators in the base scenario, although this does not explain the entire difference. The lower load factors of 49.75% do however suggest lower profitability, although it remains profitable for the operator with a plus of around €2 517 000, which is about a quarter of the sum of the individual operators of the basic scenario (€9 855 000).

Table 5-11: Network KPIs of centralised single-operator scenario

Network KPIs	**Unit**	**E1 (Baseline)**	**E4 (centralised profit-maximisation)**	**E5 (Centralised demand-maximisation)**
Number of active lines	[no. lines]	169	159	575
Number of active services	[no. lines]	231	159	575
Number of used edges	[no. edges]	196	169	222
Number of reachable ODs	[no. city pairs]	2 747	2838	2838
Train-kms	[10^3 km]	712.67	732.56	2 516.73
Average stops per line	[no. stops]	4.31	5.05	5.38
Average stops per service	[no. stops]	4.73	5.05	5.38
Average line length	[km]	783	925.47	900
Average service length	[km]	849	925.47	900
Network Connectivity	[-]	0.540	0.466	0.612

Table 5-12: Passenger KPIs of centralised operator scenario

Passenger KPIs	**Unit**	**Baseline value**	**Centralised operator: profit maximisation**	**Centralised operator: demand maximisation**
Percentage of unserved demand	[pax] & [%]	98 599 (23.76%)	117 968 (27.94%)	8 741 (1.97%)
Percentage of served demand	[pax] & [%]	316 388 (76.24%)	304 282 (72.06%)	434 011 (98.03%)
Share of served demand that can be served without any transfers	[pax] & [%]	206 104 (65.14%)	198 736 (65.31%)	321 197 (74.00%)
Share of served demand that can be served with 1 transfer	[pax] & [%]	82 624 (26.11%)	81 295 (26.72%)	98 604 (22.72%)
Share of served demand that can be served with 2 transfers	[pax] & [%]	22 740 (7.19%)	19 627 (6.45%)	13 158 (3.03%)
Share of served demand that can be served with 3+ transfers	[pax] & [%]	4 919 (1.55%)	4 624 (1.52%)	1 051 (0.24%)
Passenger-kms	[10^6 km]	195.22	192.34	271.77
Average travel distance per passenger	[km]	617.03	632.12	626.17
Average travel time per passenger	[min]	205.80	209.24	204.08

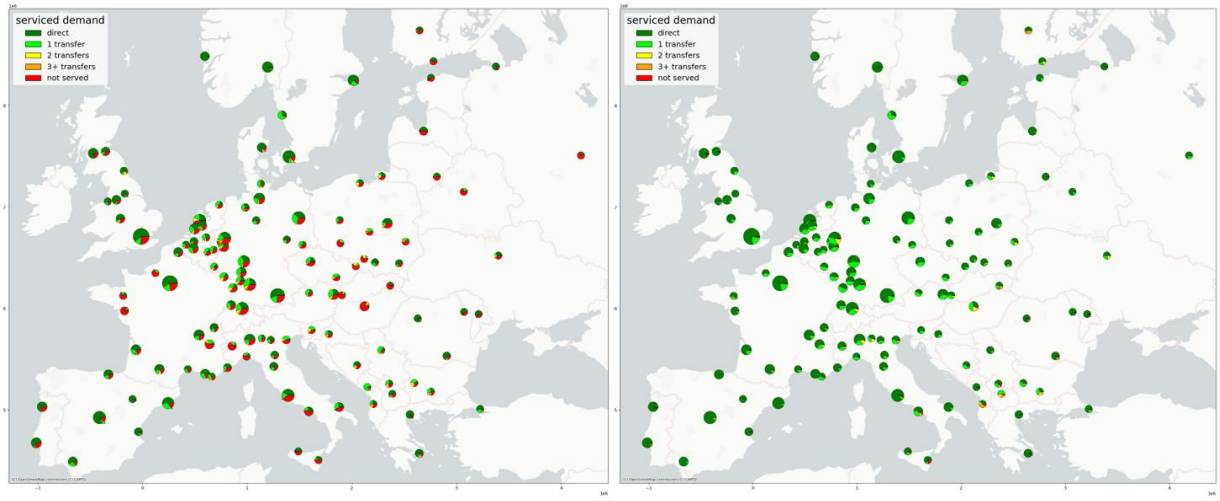


Figure 5.14: Shares of served passenger demand for each node for E4 and E5. The size represents the total demand

Table 5-13: Operator KPIs for centralised single operator scenarios

Operator KPIs	**Unit**	**Centralised operator: profit maximisation**	**Centralised operator: demand maximisation**
Profits	[10^3 €]	8 797.84	2 516.73
Load factors	[%]	65.64	49.75

5.2.3 Sensitivity analysis

Entry costs

The entry costs k^{entry} as discussed in Subsection 4.2.3 had to be selected arbitrarily as it is exclusively used for modelling purposes. Therefore, a sensitivity analysis is conducted on that parameter to see how changes in this value impact some of the KPIs. Specifically of interest are the active services, service length, the total train-kilometres, and the served demand. The values selected are 10 000, 25 000, 50 000, 90 000, 120 000 and 150 000 € next to the baseline value of 70 000. For each value selected, the model is run as standard until convergence or the maximum 50 iterations are reached. Both 10 000 and 25 000 did not converge within the 50 iterations, while for the other values convergence was found within 6 to 15 iterations.

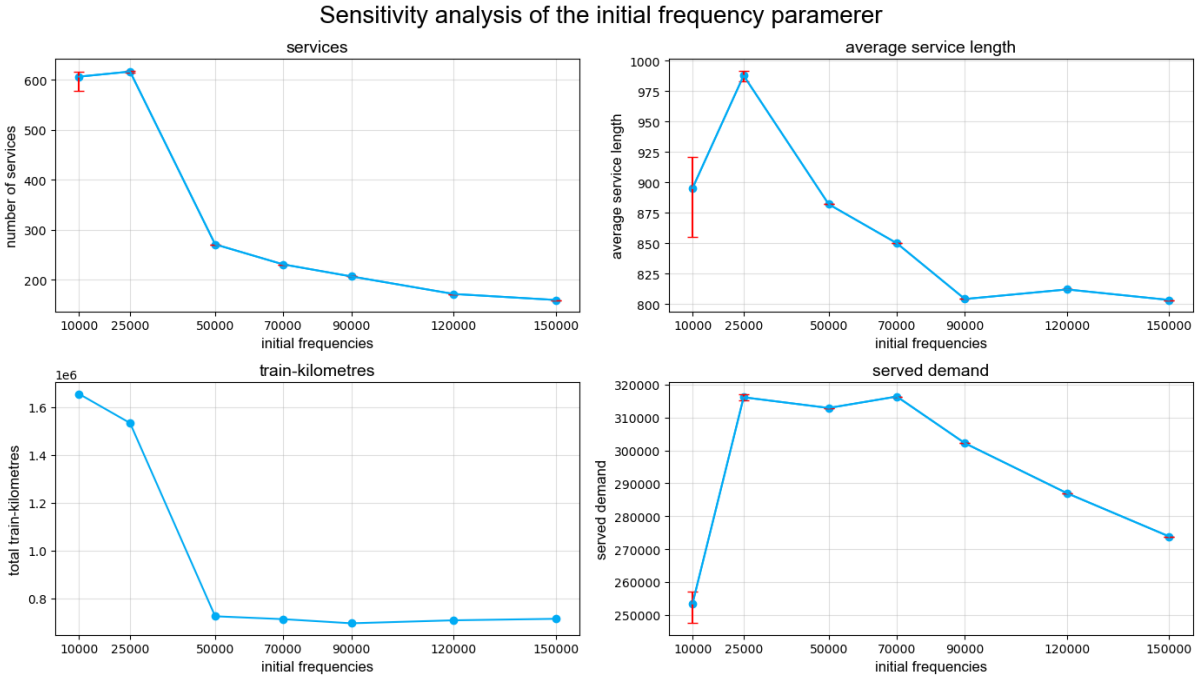


Figure 5.15: Sensitivity analysis of the entry cost parameter k^{entry}

Figure 5.15 shows that the number of services generally gets lower the higher the entry costs are. This is not surprising as more services directly means higher entry costs. Service length does not completely follow the k^{entry} pattern, especially with k^{entry} = 25 000 having a significantly longer length than k^{entry} = 10 000. In general, the higher values lead to shorter average services, which is caused by the initial lines being shorter than what operators select, meaning that when there are less new services these shorter initial lines have a higher weight on the mean length. Looking at the full KPI results in Appendix B.1, this also holds true for the number of stops. The train-kilometres have a large decrease from the lowest two values

compared to the rest, being relatively even for 50 000 and onwards. Finally, the served demand has an interesting pattern, where the lowest k^{entry} performs the worst, the three until 70 000 are similar, before there is a linear decrease for 90 000 up to 150 000. The bad performance from k^{entry} = 10 000 is likely caused by problems with the demand assignment, while the decreasing performance for the higher values is caused by the lower number of lines.

This sensitivity analysis suggests that the value of k^{entry} has a sizeable impact on the final outcome of the model, with the lower values leading to problems of model convergence, but the higher values leading to a higher dependency on the initial operator networks.

Initial frequencies

Setting different initial daily frequencies $f_{sl}^{initial}$ for all the national operators leads to differences in the initial budgets, which is the other parameter which had to be set arbitrarily. The values were set to 3, 6, 9, 15 and 18 next to the baseline value of 12. All of the runs converged within 7 to 14 iterations.

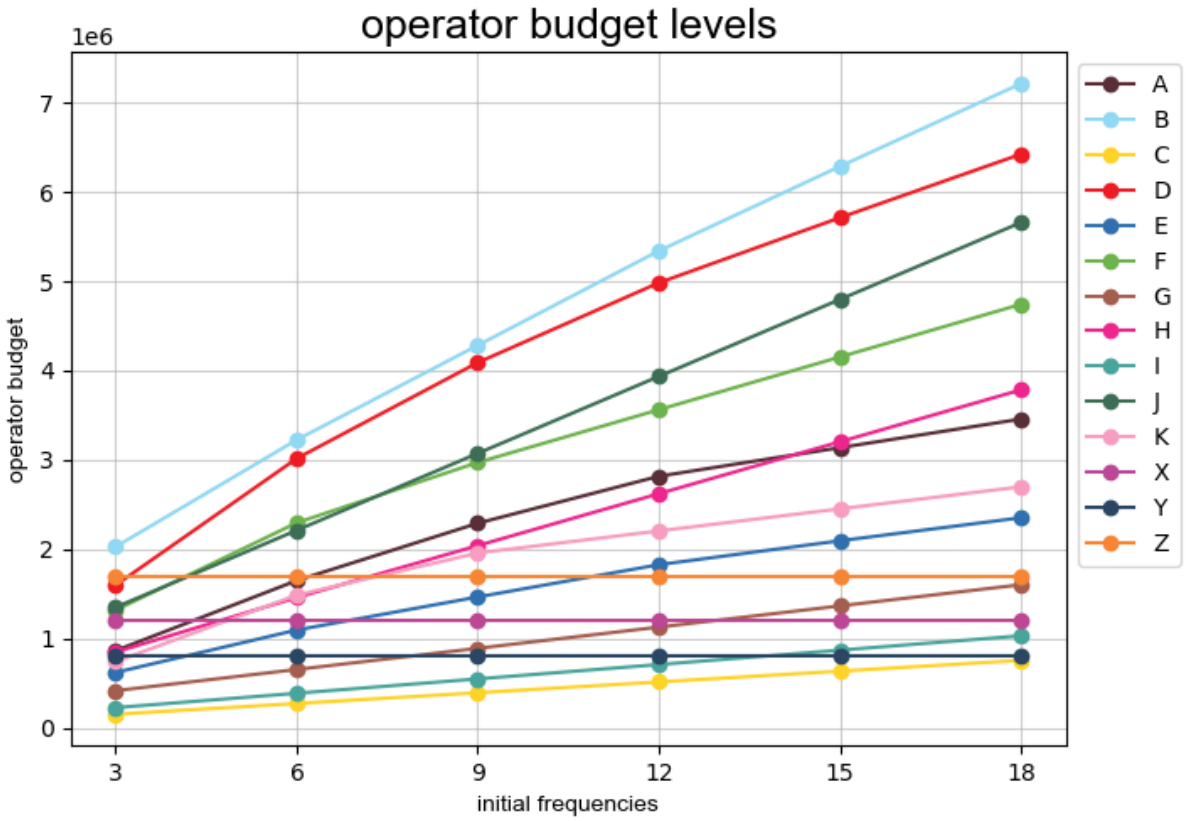


Figure 5.16: operator budget levels relative to the initial frequencies

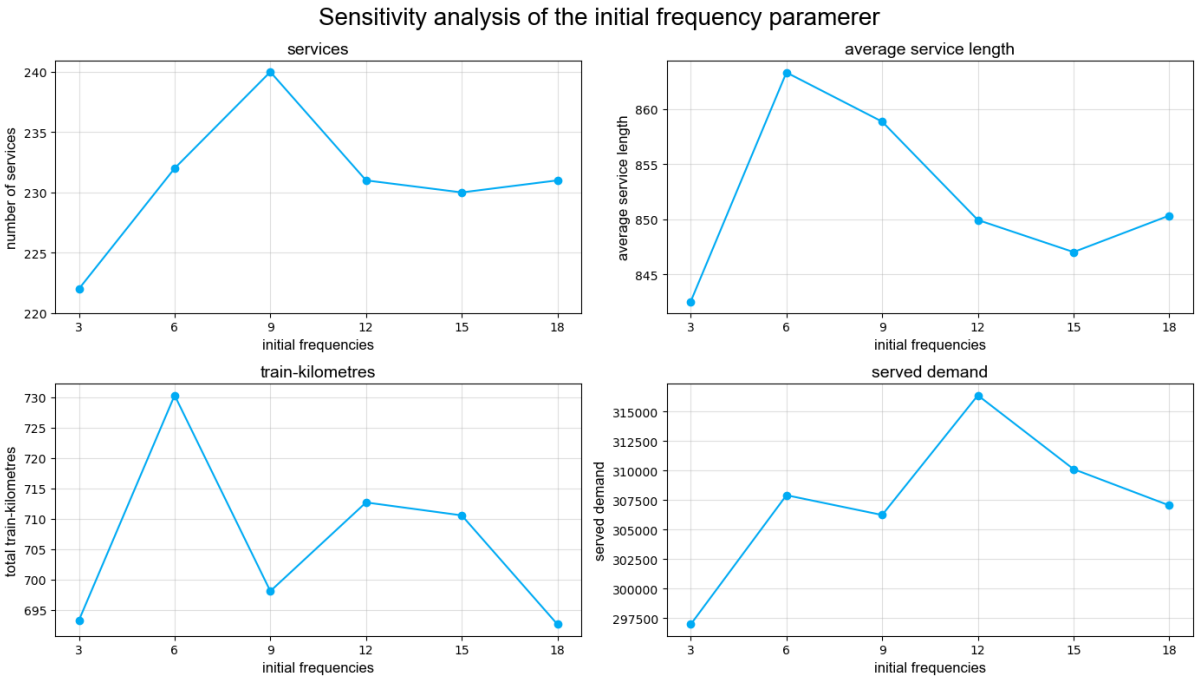


Figure 5.17: Sensitivity analysis of the initial daily frequencies $f_{sl}^{initial}$

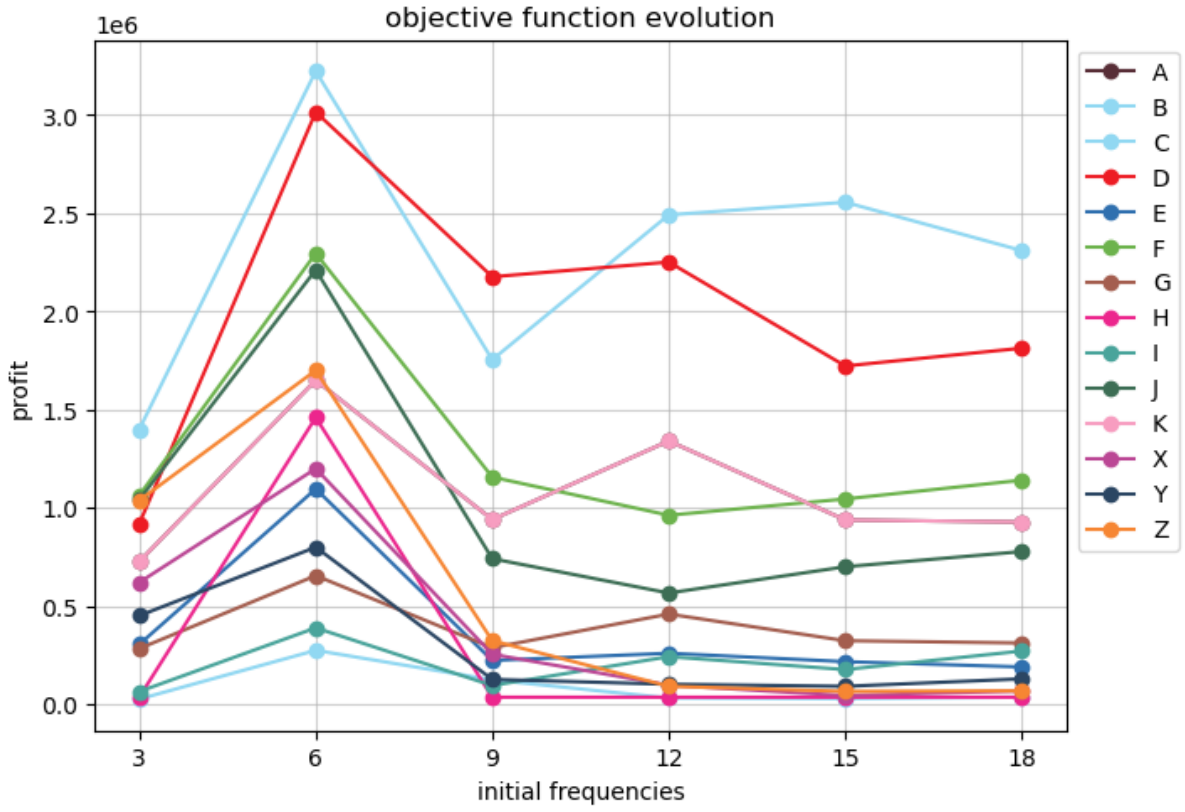


Figure 5.18: Sensitivity analysis of operator profits for the initial daily frequencies $f_{sl}^{initial}$

The initial frequencies impact budget substantially, with the budgets increasing three- to fivefold from the lowest (3) to the highest (18) initial frequencies (Figure 5.16). These budgets do not seem to lead to a pattern for the KPIs examined as seen in Figure 5.17. Even with more budget, there are no more services or train-kilometres. The served demand also does not

increase directly with budget. Operator profits at the last iteration, as shown in Figure 5.18 do not increase with higher initial frequencies and budgets, and actually have their highest values at $f_{sl}^{initial} = 6$. Combined with the patterns of the operator results being consistent for all scenarios, this suggests that budget seems to be most impactful on the relative expansion power of operators, but isn't in the end the main limiting factor, and shows further that there seems to be issues with the demand assignment.

No enforced initial network

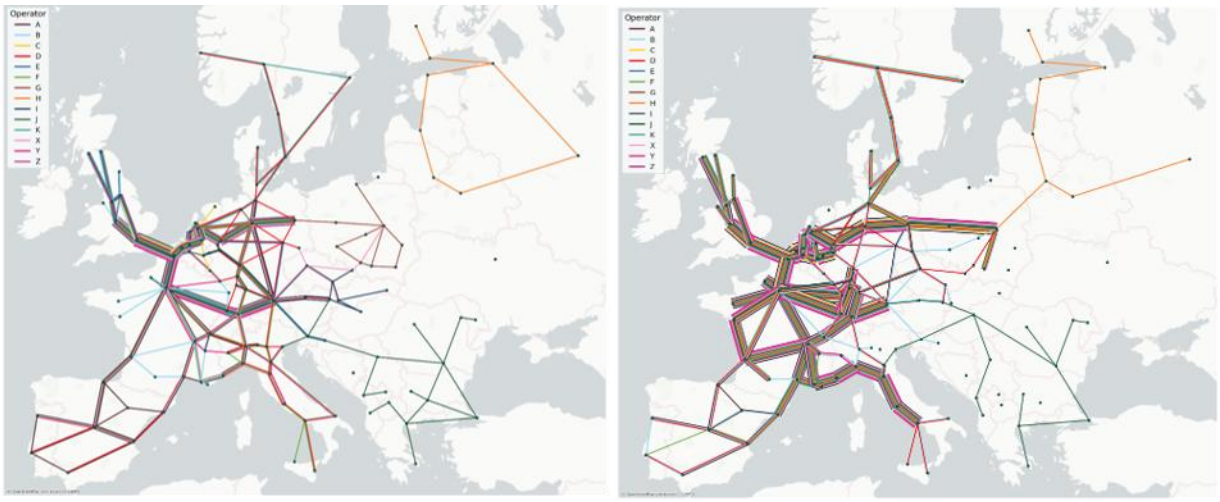


Figure 5.19: Line network for experiment with no enforced networks for k^{entry} = 70 000 (left) and k^{entry} =10 000 (right)

The experiments not enforcing the initial networks of national operators could be expected to make parts of the network lose service. For k^{entry} = 70 000, as seen on the left of Figure 5.19, this is only the case for three cities in the network: Sarajevo, Kaliningrad and Kyiv. The network is otherwise structurally very similar to the baseline scenario. Even when there is no restriction, operators largely retain their initial network. Using k^{entry} = 10 000 (which like the previous networks did not fully converge after 50 iterations and 26 hours), operators are more likely to stop serving a more nodes (12 are not served) and instead concentrate on the corridors in western Europe, with multiple lines taken by all 14 operators. This shows that, with complete freedom to seek the maximum profit, operators might completely abandon areas of the network.

6 Discussion

This Chapter discusses the results of the experiments, with Section 6.1 presenting the interpretation of these results. Section 6.2 discusses the implications of this research for policymakers, and Section 6.3 delves into the limitations and shortcomings of the model, both regarding the assumptions made as well as the methodological implementation. Finally, Section 6.4 makes recommendations for future research based on the shortcomings and gaps.

6.1 Interpretation of the results

The central finding of this study is that liberalisation and opening with profit-seeking operators leads to higher and more diversified supply of transport in corridors with sufficiently high demand. This is consistent with the case study findings in Europe discussed in Section 2.1 such as Bergantino et al. (2015), Tomeš et al. (2016), Vigren (2017) among others. This better supply leads to high passenger benefits in these areas, with high, diversified supply of long-distance rail, a lot of which with direct connections (>60%), which in turn induces further demand. While this could not be verified using this model, this higher demand could be attracted from more polluting alternatives such as flying, which is a part of the intended goals of the European Union's liberalisation policies (Broman & Eliasson, 2019; European Commission, 2025).

However, the focus on high demand areas leads to a depletion of supply in areas with less demand, with a large part of the nodes in Eastern Europe being served with only lower levels of service or even disconnected from the rest of the network. This is more caused by profit-maximisation than the competition in itself. The outcomes are partly consistent with literature warning about the liberalisation leading to a lowering of frequencies in less profitable parts of the network, caused by lack of money to cross-subsidies these lines (Bergantino et al., 2015; Moyano & Dobruszkes, 2025; Steer Davies Gleave, 2016), though the cross-subsidy mechanism itself was not investigated in this research.

Increasing coordination between the operators, another policy of the European Commission (Directorate-General for Mobility and Transport, 2026) can also be found to marginally increase passenger benefits with increased levels of service compared to the lower-coordination scenarios. Operators, on the other hand, benefit less in terms of profits from this coordination, with lower profitability. The improvements are however relatively small, and the way competition is modelled is very simplified with a simple penalty. Thus, these findings also require more scrutiny.

Finally, testing for a singular operator shows that the network of the singular profit-maximiser is similar to the baseline with competing operators. This leads to the conclusion that within the model the profit-maximisation aspect is the main driver behind the strong regional differences within the network, more so than the competition between the operators itself. Competition even leads to a slightly better passenger performance. Modelling the centralised operator as being demand-maximising leads to an even more extensive network, but at the cost of some profits, although it remains profitable. This does however not include the costs of construction of the infrastructure to allow for the speeds in the available data, which is likely to outweigh these profits, though as in Grolle (2020), societal benefits such as reduced pollution and

accidents can counteract these costs again. Further analysis would be needed to investigate these societal costs and benefit aspects for this network.

6.2 Policy implications

The finding of this research can be used to formulate some recommendations for policymakers working on the liberalisation of passenger rail in the EU: Firstly, the main difference maker in passenger performance is the service objective and not the market structure. Indeed, attempting to maximise demand through a centrally planned operator instead of profits leads to a much better performance, while still remaining economically viable. However, due to the political structure of the EU and its sovereign states with its different operators (as well as the non-EU states central to this network either by their high international demand like the United Kingdom or their geographical position like Switzerland), such a centralised structure seems unlikely. Additionally, this does not consider the upfront costs of getting the network up to the state of interoperability assumed in this thesis. If the network is to be further opened up, a key aspect behind a well-performing network is to increase the coordination between operators in terms of ticketing as well as scheduling to allow for seamless transferring for passengers looking to take the train for international trip. This would improve the position of rail as an option for these international trips.

Secondly, a careful balance is required to prevent an increase in regional inequalities when implementing this liberalisation. As could be seen in this study, areas with lower demand are all left to close to minimum levels of service due to a lack of profitability, while the highest demand areas see their service quality to massively increase. In the long term, these lower-demand areas could find themselves with a lack of services due to operators not being able to cross-subsidise these unprofitable lines due to competition reducing their profits on the lines that are actually profitable. A possible solution to this could be in the form of subsidies from the EU to the respective operators to continue operating these lines, although just like for the previous point, not all countries most concerned by this (Türkiye, Ukraine, Russia) are part of the EU.

6.3 Limitations and shortcomings of the model

There are a range of limitations associated with the model used in this research, owing to the number of simplifications and assumptions made, as well as some methodological shortcomings.

Excluding price from the model was necessary in order to viably implement it in the scope of this research, but it is a very large omission when researching any kind of competition. As found in 2.1 and 2.2, differentiation in price is the main tool new operators can use to compete with the existing national incumbents, which also has large impacts on how passenger demand is captured. Not including price makes it also hard to differentiate between the operators in this model in other ways than budget and initial location, since the objective function was also taken as the same for all operators.

The assumption that operators can capture demand abroad equally to the incumbent operator works for this model but in reality, the barriers are larger, especially concerning cross-border ticketing which negatively impacts operator revenue (Whitaker et al., 2026). Travellers might be reticent to opt for these new services if the pricing difference isn't large enough due to passengers' preferences for domestic rather than international services (Rietveld, 2012).

Cases like the one in Slovakia discussed in Section 2.1 (Kvizda & Solnička, 2019), where incumbent operators are advantaged by local policies, lead to the same outcome of worse demand for external operators. European policies intend to reduce the monopolies of incumbents and avoid this kind of non-competitive behaviour, but these actions cannot be completely excluded. In the long-term, if policies such as the ticketing unification as well as other interoperability standards are fulfilled, these issues could be largely compensated for.

Paths on longer routes are assumed to bring an operator more revenue from a passenger than the direct shortest one, as they cover more kilometres. In reality, passengers would be willing to spend more money for a shorter trip and thus the operator would charge higher fares. This would however be more complicated to implement for paths using lines by multiple operators.

Of importance especially for the single-operator scenarios, but also already for the multiple operators, the stakeholder perspective of the European Union itself, and the additional subvention costs that it would have to pay in order to coordinate and plan are not included.

Beyond the overly strong assumptions, this research also shows some clear weaknesses in the modelling and selection of methods. While it is a viable methodology to investigate performance and look into potential networks, TNDFSP can hardly be used in practice to plan networks due to the number of simplifications and assumptions made in the model (Durán-Micco & Vansteenwegen, 2022a). This means that outcome of line plans presented here can hardly be used as recommendations for actual lines and frequences on the real network. There are further problems in the model especially regarding how passenger demand is handled. Passenger paths all being assumed independent of each other is not realistic for a logit model, and a different alternative of the method should have been used such as a C-logit, which takes commonality between various paths (B. Liu et al., 2020). The calculation of saturation and final assigned demand for each extended edge being done in a static way, it does not allow for spill and instead, all demand assigned to an overly saturated edge is lost and unassigned. Using an iterative method to reassign this lost demand would be more realistic, as at least a part of the passengers could be expected to take a different path even if it is not their most preferred option. This would prevent the irregularity of some of the centrally located and well-serviced nodes (such as Köln and Düsseldorf) having relatively poor served demand. While the approach of taking betweenness and assigned demand of parallel line-edges as a proxy is good in theory, in practice it seems to strongly overestimate the demand on a lot of edges, resulting in operators selecting these edges based on “wrong expectations” due to double counting of the passengers. It is also likely the reason behind most of the lines being selected with frequencies of 1. Consequently, the passenger assignment being a lot lower in terms of passenger numbers leads to the model often activating then deactivating the same few lines or edges for an operator without staying on the same line in two consecutive iterations if k^{entry} is not set relatively high. This shortcoming is discussed more in depth in subsection 6.3.1 below. The assignment seems to further have some shortcomings with how the reduction of demand is handled when edges are saturated, which is another cause of the final assigned demand to be lower than the expectation.

Further related to the demand assignment, the assigning itself takes too long to really make this method scalable to a bigger, more detailed European network in this form. A possible solution could be the bundling of passenger paths on the extended graph which do the same routes of the same operator but on different lines. This would however also require a

modification of the passenger assignment in regard to how saturation is treated, as the demand would have to be bundled then separated again to assign the demand to all the edges of each line.

While exactly solving the MILP used seemed to work fine on this model, with a denser and more detailed network the computational costs could be expected to increase rapidly. Utilising heuristic or metaheuristic methods instead would allow for more scalability. This is especially true if the line generation procedure is done in a similar fashion, resulting in a large number of lines, although this can be partially fixed by selecting a subset of terminal nodes, which are the only ones lines can originate and terminate at (as used in e.g., Cipriani et al., 2006; Grolle, 2020; Liang et al., 2019) .

Another modelling shortcoming includes the unrealistic modelling parameters, namely operator budgets b_s and entry costs k^{entry}. Budget b_s effectively limits the number of lines an operator can run on, even if there are further lines which might be profitable, although in the later iterations of the model it was found to rarely be the limiting constraint (see Section 5.2.3). For models which take into account evolution through time (see e.g., Borgogno et al., 2025), a budget limitation for each iteration, representing investment budget constraints, is perfectly realistic. For the profit-maximising optimisation without a time-component in the case of this research, this budget does not really represent any real-life constraints in the way it was modelled, as it doesn't take into account the profits generated from additional lines. Instead, it had to be put in as a modelling constraint to avoid the computational times of the linear programs from getting completely out of control (which was especially true for lower values of k^{entry}), and additionally create a bigger differentiation between the operators, as their only other difference otherwise is their initial line network. This constraint was thus necessary for this model to function, but further research should investigate alternative means of implementing budget constraints. Entry costs parameter k^{entry} shares a similar flaw in terms of being a constraint necessary for the model to function, as was briefly touched on in Section 5.2.3.

Originally, the infrastructure data was meant to be the TEN-T rail network for a future year 2050 instead of the European high-speed rail dataset from Grolle et al. (2024). This would have allowed for outcomes somewhat closer to reality with more accurate travel times between cities, as they are now much shorter than realistic times. This could unfortunately not be implemented due to data availability issues and problems with the planning timeline. Similarly, more sensitivity analyses of costs, revenue, elasticities, and the initial networks and assumptions would have been necessary due to the large number of assumptions used for the model, but these could not be implemented due to poor planning.

Finally, the data used also has a limitation of only considering demand past 100 km as it was originally meant for high-speed rail only. While this works fine for a large part of the network, the denser areas especially around the Benelux and Nordrhein-Westfalen end up with lower demand between these cities than would be realistic. A solution to this would be to implement another demand estimation method for just these shorter distances, such as for example a gravity model.

6.3.1 Issues with model oscillation

Testing with different values for k^{entry} shows weaknesses in the model, namely that the convergence is not assured and that the model frequently finds itself "oscillating" between two

network states until reaching the maximum number of iterations. This is likely caused by poor estimation of the expected demand on edges that are in use compared to edges which are not in use. Further, setting k^{entry} too low would lead to this "oscillating" between two states to be very strong from the first iterations, activating and deactivating large numbers of lines in

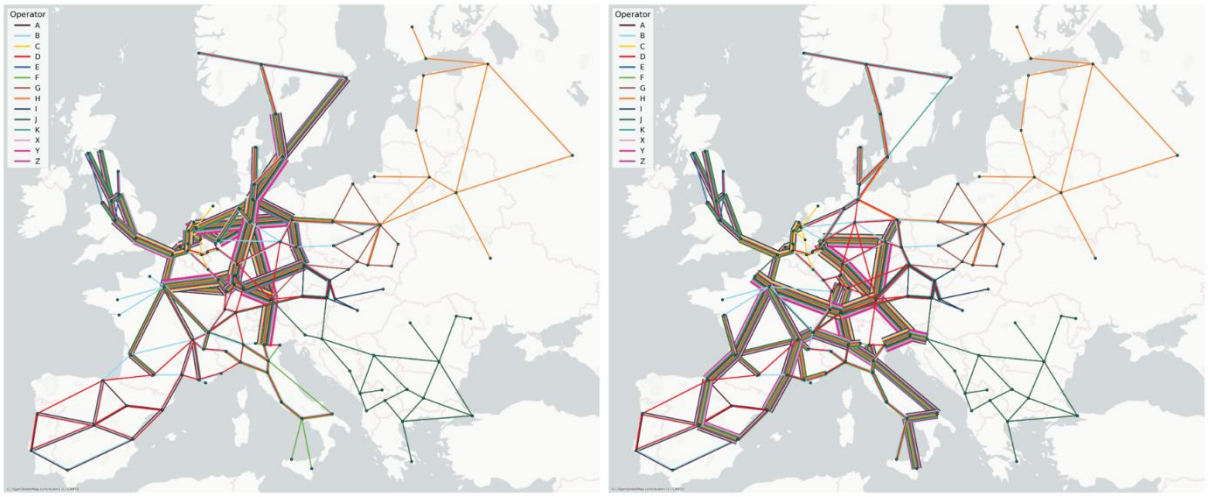


Figure 6.1: example of oscillating of the line selection between two successive iterations

corridors in successive iterations. An example can be seen in Figure 6.1 for $k^{entry} = 10000$, the final iterations 49 and 50, where on the left lines in Germany and the Nordics go from having a large number of operators to having practically none in the following iteration (right) and conversely lines in southern Europe go from few operators to most operators operating on those. This commonly happened multiple iterations in a row. Again, this is likely caused in part by poor estimation of the expected demand on edges that are in use compared to edges which are not in use, but also by the simultaneous nature of the decisions taken by operators, meaning that if a line is attractive to the operators they are likely to all select it if possible, which in turn makes it too saturated to be attractive in the following iteration. In addition, operators seem to set a lot of lines with a low frequency, which increases the demand assignment times due to the increased number of line-edges. Setting a higher k^{entry} (around 100 000) reduces these problems as operators are more "stuck" to their networks, however problems arise with the operators with smaller budgets, where in solving the MILP the high k^{entry} makes adding new lines very unlikely unless the returns are very high, meaning these operators remain unable to add more lines. A high k^{entry} thus leads to a higher path-dependency where the starting networks of operators heavily influence the final network outcome.

Even without low k^{entry} values and large oscillating as shown in the previous paragraph, it could happen with some initiation values that the model would not converge, as it would oscillate between states at a much smaller scale. One model initiation led to two operators changing the frequency of one of their lines, by only 1 frequency between each iteration, and the passenger assignment led to objective functions varying by slightly over 1% each iteration, meaning it never terminated.

6.4 Recommendations for future research

For using TNDFSP models to investigate operator competition, multiple aspects of this model could be refined. Modelling PSO operators differently to private ones, such as with a different

objective function or different incumbent advantages when operating in their respective country and disadvantages (e.g., in terms of the level of demand they attract) when abroad (Ristić et al., 2022). This could provide deeper insight than with the simple difference of “fixed network and no fixed network” used in this research. Coordination and cooperation should also be modelled in more detail, as in this research it is simply taken by modifying a singular passenger transfer parameter.

As previous TNDFSP literature has shown, utilising exact methods for TNDFSP problems can be tricky due to their NP-hard nature (Owais, 2026) and be hard to scale. While for this research the running times ended up being mostly reasonable, scaling up the model to a more detailed representation of the European network with 500+ nodes would be far too much to keep running times low, especially if the demand matrix is larger. Heuristic solution methods for the MILP and especially more efficient demand assignment method would be a priority in this regard. Better demand assignment methods and assessment of expected demand should also lead to a more realistic outcome than the ones presented in this research, especially concerning the high amount of very low frequency lines. One such improvement could be the use of a C-logit for passenger route choice, as this variation of the choice model is made to account for overlapping passenger routes. Further, the demand assignment should be done iteratively and allow for passenger spill, as in this model the reduced demand is simply left unserved. Utilising more efficient solutions would also allow for better formulation of the linear programming problem, such as outright removing the budget constraint and modifying the entry costs parameter.

For smaller instances, it could also prove viable to add to the model what is likely the biggest modelling omission of pricing, which could possibly also be solved for within the linear programming part. This could allow to explore how a network would be structured for competition between operators with different pricing strategies (be it low-cost like Flixtrain or more premium offerings like Italo) and different types of passenger demand (business vs. leisure). Literature on this is already present for single-line duopoly models (Álvarez-SanJaime et al., 2015; Cherbonnier et al., 2018; Ristić et al., 2022) and exploring its implementation into line and frequency setting models could be of interest in the liberalisation context.

7 Conclusions

In the context of an increasingly liberalised passenger railway market in the European Union, this research aimed to better understand how competition between rail operators can shape the European long-distance rail line network. This is asked with the following main research question, as formulated in chapter 1.2:

“How does a decentralised European long-distance rail network perform given competition between service providers?”

And the sub-questions:

SQ1: “What line configurations and frequencies do service providers set when competing with other providers and what network structure does this result in?”

SQ2: “To what extent is the passenger demand across the network serviced?”

SQ3: “How does the performance of the decentralised network compare to a centrally designed network in terms of the lines, frequencies, and serviced demand?”

SQ4: “How do different levels of inter-operator coordination impact the network outcomes?”

These questions were all answered using a Transport Network Design and Frequency Setting Problem (TNDFSP) methodology described in Chapter 3 with experiments elaborated on in sections 4.2 and 4.3.

SQ1 gets answered through experiments E1-E3, where each time the final network has a few key characteristics: a very dense, highly diverse line network around a lot of western/northwestern Europe with most operators congregating around that area, coming at the costs of service being practically at a minimum across especially the east of the network. The lines selected are long (majority 700-1200km) and mostly run with low (<3) daily frequencies. In the high-density areas these bundle together to give passengers high frequency on the corridors while keeping a lot of potential direct connections. Northeastern Europe ends up as a separate subnetwork. In low demand areas, the services still being intact is partly thanks to the restriction forcing operators to keep their initial network.

For SQ2, the baseline experiment shows that around 75% of the total demand is served in total, but with large geographical differences. It is served relatively well in the high-density areas for the biggest cities such as London, Paris and München, but the best served cities are midsized cities well-located on corridors such as Valencia, or on the edge of the network with high demand and large distances which equals to high passenger-kilometres, such as Bergen and Oslo. Poorly serviced cities are those in the disconnected part of the network (e.g., Kyiv, Kaliningrad), with served demand as low as 10-20%. Some well-served cities such as Köln and Düsseldorf end up with relatively poorly served demand (60-65%), which is partly due to issues with how the passenger demand assignment is modelled and how demand that is beyond edge capacity gets rejected instead of being reassigned

For SQ3, the network of the first three experiments can be compared to experiments 4 and 5, which shows that a centralised single-operator network with demand-maximisation generally performs better in terms of served passengers (98% demand served) while still remaining profitable, although at four times lower profit margins than for the competition. The profit-

maximising operator ends up with a similar network, but with slightly worse passenger performance, suggesting that the decisive aspect is the policy goal and not the market structure.

Finally, SQ4 is answered looking at experiments 2 and 3, where it is visible that changes in coordination between operators are only marginally impactful, where erasing the barriers between operators completely, increases the train-kilometres by about 7% and total served demand by about 2%, but lowers operator profits. E3 shows that a lower coordination results in a very similar network to the baseline, suggesting that coordination does not impact the outcomes of this model much.

To conclude, while this research cannot be used as a practical recommendation to operators for line network design due to the high number of assumptions and simplifications, it gives some indication about how a liberalisation of the European network could impact said line network. These findings must however be observed critically and are strongly influenced by the modelling used in this research.

References

Adler, N. (2001). Competition in a deregulated air transportation market. *European Journal of Operational Research*, (129), 337–345. www.elsevier.com/locate/dsw

Adler, N. (2005). Hub-spoke network choice under competition with an application to Western Europe. *Transportation Science*, *39*(1), 58–72. https://doi.org/10.1287/trsc.1030.0081

Adler, N., Brudner, A., & Proost, S. (2021). A review of transport market modeling using game-theoretic principles. *European Journal of Operational Research*, *291*(3), 808–829. https://doi.org/10.1016/j.ejor.2020.11.020

Adler, N., Pels, E., & Nash, C. (2010). High-speed rail and air transport competition: Game engineering as tool for cost-benefit analysis. *Transportation Research Part B: Methodological*, *44*(7), 812–833. https://doi.org/10.1016/j.trb.2010.01.001

Albuquerque, J., Gomes, M. C., Olivé, J. M., & Andrade, A. R. (2026). Transit network design and frequency setting with elastic demand: a mixed-integer linear programming approach. *Transportation Research Part A: Policy and Practice*, *212*. https://doi.org/10.1016/j.tra.2026.105156

Alstom. (n.d.). *Avelia Horizon: The most advanced double-deck high-speed train in the world*. Retrieved October 26, 2026, from https://www.alstom.com/solutions/rolling-stock/high-speed-trains/avelia-horizon-most-advanced-double-deck-high-speed-train-world

Álvarez-SanJaime, Ó., Cantos-Sanchez, P., Moner-Colonques, R., & Sempere-Monerris, J. J. (2015). A model of internal and external competition in a High Speed Rail line. *Economics of Transportation*, *4*(3), 178–187. https://doi.org/10.1016/j.ecotra.2015.05.004

Álvarez-SanJaime, Ó., Cantos-Sanchez, P., Moner-Colonques, R., & Sempere-Monerris, J. J. (2016). Rail access charges and internal competition in high speed trains. *Transport Policy*, *49*, 184–195. https://doi.org/10.1016/j.tranpol.2016.04.006

Antoniazzi, F., Giuricin, A., & Tosatti, R. (2020). Introducing competition in Italian high-speed rail. *L'Espace Géographique*, *Tome 48*(4), 329–349. https://doi.org/10.3917/eg.484.0329

Battilocchi, T., Beria, P., & Pařil, V. (2026). The third phase of the liberalisation of European long-distance passenger railways. *European Transport Studies*, *3*. https://doi.org/10.1016/j.ets.2026.100067

Behrens, C., & Pels, E. (2012). Intermodal competition in the London-Paris passenger market: High-Speed Rail and air transport. *Journal of Urban Economics*, *71*(3), 278–288. https://doi.org/10.1016/j.jue.2011.12.005

Bergantino, A. S., Capozza, C., & Capurso, M. (2015). The impact of open access on intra- and inter-modal rail competition. A national level analysis in Italy. *Transport Policy*, *39*, 77–86. https://doi.org/10.1016/j.tranpol.2015.01.008

Beria, P., Crozet, Y., & Guihery, L. (2025). Competition models and financial sustainability of high-speed open-access passengers rail operators in Europe. *European Transport Studies*, *2*. https://doi.org/10.1016/j.ets.2024.100008

Beria, P., Lunkar, V., Tolentino, S., Pařil, V., & Kvasnička, M. (2023). Long-distance rail in Europe: Comparing the forms of head-on competition across Europe. *Research in Transportation Economics*, *102*. https://doi.org/10.1016/j.retrec.2023.101367

Borgogno, F., Massobrio, R., Grolle, J., & Cats, O. (2025). *European High-Speed Rail Infrastructure: A network evolution approach*. https://doi.org/10.21203/rs.3.rs-7252650/v1

Brenna, C. (2024). Price impact of high-speed rail competition between multiple full-service and low-cost operators on less congested corridors in Spain. *Transport Policy*, *156*, 77–88. https://doi.org/10.1016/j.tranpol.2024.07.013

Broman, E., & Eliasson, J. (2019). Welfare effects of open access competition on railway markets. *Transportation Research Part A: Policy and Practice*, *129*, 72–91. https://doi.org/10.1016/j.tra.2019.07.005

Canca, D., De-Los-Santos, A., Laporte, G., & Mesa, J. A. (2019). Integrated Railway Rapid Transit Network Design and Line Planning problem with maximum profit. *Transportation Research Part E: Logistics and Transportation Review*, *127*, 1–30. https://doi.org/10.1016/j.tre.2019.04.007

Cascetta, E., & Coppola, P. (2014). Competition on Fast Track: An Analysis of the First Competitive Market for HSR Services. *Procedia - Social and Behavioral Sciences*, *111*, 176–185. https://doi.org/10.1016/j.sbspro.2014.01.050

Cats, O. (2025). The long journey towards a shift to rail in the European long-distance passenger transport market. *Npj Sustainable Mobility and Transport*, *2*(1). https://doi.org/10.1038/s44333-025-00025-9

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

Chakroborty, P. (2003). Genetic Algorithms for Optimal Urban Transit Network Design. In *Computer-Aided Civil and Infrastructure Engineering* (Vol. 18).

Chen, M., & Souche Le Corvec, S. (2019). On the Usefulness of a Combined Mode Choice-Schedule Choice Model: Case of the Paris–Bordeaux Rail Line (France). *Transportation Research Record*, *2673*(4), 697–707. https://doi.org/10.1177/0361198119837958

Cherbonnier, F., Ivaldi, M., Muller-Vibes, C., Van, K., & Straeten, D. (2018). *Competition For Versus In the Market of Long-Distance Passenger Rail Services*.

Cipriani, E., Petrelli, M., & Fusco, G. (2006). A multimodal transit network design procedure for urban areas. In *Advances in Transportation Studies an international Journal Section A* (Vol. 10).

de Rose, A., Trier Jørgensen, K., & Doklestic, N. (2024). *Study on passenger and freight rail transport services' prices for final customers Final Report*. https://op.europa.eu/publication-detail/-/publication/4ea76998-7955-11ef-bbbe-01aa75ed71a1

Derrible, S., & Kennedy, C. (2010). The complexity and robustness of metro networks. *Physica A: Statistical Mechanics and Its Applications*, *389*(17), 3678–3691. https://doi.org/10.1016/j.physa.2010.04.008

Desmaris, C., & Croccolo, F. (2018). The HSR competition in Italy: How are the regulatory design and practices concerned? *Research in Transportation Economics*, *69*, 290–299. https://doi.org/10.1016/j.retrec.2018.05.004

Dijkstra, E. W. (1959). A Note on Two Problems in Connexion with Graphs. In *Numerische Mathematik ~*.

Directorate-General for Mobility and Transport. (2026, May 13). *One journey, one ticket, full rights: Commission simplifies Europe-wide travel booking and train travel*. https://transport.ec.europa.eu/news-events/news/one-journey-one-ticket-full-rights-commission-simplifies-europe-wide-travel-booking-and-train-travel-2026-05-13_en

Donners, B. (2016). *Erasing borders European Rail Passenger Potential*. Delft University of Technology.

Doyme, K., Dray, L., O'Sullivan, A., & Schäfer, A. (2019). Simulating Airline Behavior: Application for the Australian Domestic Market. *Transportation Research Record*, *2673*(2), 104–112. https://doi.org/10.1177/0361198119826533

Durán-Micco, J., & Vansteenwegen, P. (2022a). A survey on the transit network design and frequency setting problem. *Public Transport*, *14*(1), 155–190. https://doi.org/10.1007/s12469-021-00284-y

Durán-Micco, J., & Vansteenwegen, P. (2022b). Transit network design considering link capacities. *Transport Policy*, *127*, 148–157. https://doi.org/10.1016/j.tranpol.2022.08.018

European Commission. (n.d.). *Trans-European Transport Network (TEN-T)*.

European Commission. (2025). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Connecting Europe through High-Speed Rail*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52025DC0903

European Environment Agency. (2026). *Sustainability of Europe's mobility systems 2025*. https://doi.org/doi:10.2800/4890019

European Parliament. (2016, April 20). *Agreement on opening up of the EU passenger railway market*. https://www.europarl.europa.eu/news/en/press-room/20160420IPR24132/agreement-on-opening-up-of-the-eu-passenger-railway-market

Fan, W., & Machemehl, R. B. (2008). Tabu Search Strategies for the Public Transportation Network Optimizations with Variable Transit Demand. In *Computer-Aided Civil and Infrastructure Engineering* (Vol. 23).

Farahani, R. Z., Miandoabchi, E., Szeto, W. Y., & Rashidi, H. (2013). A review of urban transportation network design problems. *European Journal of Operational Research*, *229*(2), 281–302. https://doi.org/10.1016/j.ejor.2013.01.001

Filgueiras, M., Gkiotsalitis, K., Yap, M., Cats, O., Lobo, A., & Ferreira, S. (2023). Bus Network Design and Frequency Setting in the Post-COVID-19 Pandemic: The Case of London. *Journal of Transportation Engineering, Part A: Systems*, *149*(4). https://doi.org/10.1061/jtepbs.teeng-7176

Flix. (2026, October 13). *Ausblick 2027: FlixTrain kündigt das beste Netz aller Zeiten an* . https://corporate.flix.com/de/press_releases/flixtrain-ausblick-2027/

Freeman, L. C. (1977). *A Set of Measures of Centrality Based on Betweenness* (Vol. 40, Number 1).

Gallo, M., Montella, B., & D'Acierno, L. (2011). The transit network design problem with elastic demand and internalisation of external costs: An application to rail frequency optimisation. *Transportation Research Part C: Emerging Technologies*, *19*(6), 1276–1305. https://doi.org/10.1016/j.trc.2011.02.008

Grolle, J. (2020). *A Unified Design of the European High-Speed Rail Network Impacts of Design, Pricing and Governance Strategies* [Master Thesis, Delft University of Technology]. https://repository.tudelft.nl/

Grolle, J., Donners, B., Annema, J. A., Duinkerken, M., & Cats, O. (2023). *Data underlying the publication: Service Design and Frequency Setting for the European High-Speed Rail Network*.

Grolle, J., Donners, B., Annema, J. A., Duinkerken, M., & Cats, O. (2024). Service design and frequency setting for the European high-speed rail network. *Transportation Research Part A: Policy and Practice*, *179*. https://doi.org/10.1016/j.tra.2023.103906

Guan, H., Basciftci, B., & Van Hentenryck, P. (2026). *Bilevel Optimization and Heuristic Algorithms for Integrating Latent Demand into the Design of Large-Scale Transit Systems*. https://doi.org/10.1287/trsc.2025.0194

Guihaire, V., & Hao, J. K. (2008). Transit network design and scheduling: A global review. *Transportation Research Part A: Policy and Practice*, *42*(10), 1251–1273. https://doi.org/10.1016/j.tra.2008.03.011

Hansen, M. (1990). AIRLINE COMPETITION IN A HUB-DOMINATED ENVIRONMENT: AN APPLICATION OF NONCOOPERATIVE GAME THEORY. *Tranrprt. Res.-6.*, *248*(Vol. 24B, No. 1), 27–43.

Hartleb, J., Schmidt, M., Huisman, D., & Friedrich, M. (2021). Modeling and solving line planning with integrated mode choice. *SSRN Electronic Journal*. https://nos.nl/artikel/2344006-ns-lijdt-185-miljoen-verlies-door-corona.html,

Heyken Soares, P. (2020). *Three Steps Towards Practical Application of Public Transport Route Optimisation in Urban Areas* [Doctoral Dissertation, University of Nottingham]. https://doi.org/DOI:10.13140/RG.2.2.24062.20802

Heyken Soares, P., Mumford, C. L., Amponsah, K., & Mao, Y. (2019). An adaptive scaled network for public transport route optimisation. *Public Transport*, *11*(2), 379–412. https://doi.org/10.1007/s12469-019-00208-x

Hughes, R. A. (2023, December 29). New destinations and Eurostar rivals: How Channel Tunnel rail travel might change in the future. *Euronews*. https://www.euronews.com/2025/12/31/new-destinations-and-cheaper-tickets-how-channel-tunnel-rail-travel-might-change-in-the-fu

Independent Regulators' Group Rail. (2024). *12 th Annual Market Monitoring Report*. https://irg-rail.eu/irg/news/press-release/406,Twelfth-Annual-Market-Monitoring-Report-published.html

italo. (2026, July 20). *ITALO INVEST 3.6 BILLION IN GERMANY AND SIGNS WITH SIEMENS AN AGREEMENT OF APPROXIMATELY 3 BILLION FOR 26 TRAINS FOR GERMANY, WITH AN OPTION FOR ADDITIONAL 14 UNITS, AND 30 YEARS OF MAINTENANCE*. https://italospa.italotreno.it/en/press-office/press-releases/2026/italo-investe-3-6-miliardi-di-euro-in-germania-e-firma-il-contratto-con-siemens-da-circa-3-miliardi-26-treni-per-il-mercato-tedesco-con-opzione-per-ulteriori-14-e-30-anni-.html

Ivaldi, M., & Vibes, C. (2007). *PRICE COMPETITION IN THE INTERCITY PASSENGER TRANSPORT MARKET: A SIMULATION MODEL Acknowledgement We are grateful to two anonymous referees*.

Janić, M. (2016). A multidimensional examination of performances of HSR (High-speed rail) systems. *Journal of Modern Transportation*, *24*(1), 1–21. https://doi.org/10.1007/s40534-015-0094-y

Johnson, D., & Nash, C. (2012). Competition and the provision of rail passenger services: A simulation exercise. *Journal of Rail Transport Planning and Management*, *2*(1–2), 14–22. https://doi.org/10.1016/j.jrtpm.2012.09.001

Kepaptsoglou, K., & Karlaftis, M. (2009). Transit Route Network Design Problem: Review. *JOURNAL OF TRANSPORTATION ENGINEERING*, (135), 491–505. https://doi.org/10.1061/ASCE0733-947X2009135:8491

Kiliç, F., & Gök, M. (2014). A demand based route generation algorithm for public transit network design. *Computers & Operations Research*, (51), 21–29. https://doi.org/DOI:10.1016/j.cor.2014.05.001

Kvizda, M., & Solnička, J. (2019). Open access passenger rail competition in Slovakia – Experience from the Bratislava–Košice line. *Journal of Rail Transport Planning and Management*, *12*. https://doi.org/10.1016/j.jrtpm.2019.100143

Laroche, F. (2024). Goodbye monopoly: The effect of open access passenger rail competition on price and frequency in France on the high-speed paris-Lyon line. *Transport Policy*, *147*, 12–21. https://doi.org/10.1016/j.tranpol.2023.09.019

Laroche, F., & Lamatkhanova, A. (2022). Effects of open access competition on prices and frequencies on the interurban railway market: Evidence from Europe. *Research in Transportation Business and Management*, *43*. https://doi.org/10.1016/j.rtbm.2021.100705

Lestari, P. D. R., Liu, R., & Batley, R. (2026). A demand response to line planning. *Multimodal Transportation*, *5*(2). https://doi.org/10.1016/j.multra.2025.100285

Li, M., Birolini, S., & Ribeiro, N. A. (2026). Hub competition and demand modeling in long-haul aviation markets: A forward-looking scenario-based game-theoretical approach. *Transportation Research Part E: Logistics and Transportation Review*, *211*. https://doi.org/10.1016/j.tre.2026.104894

Liang, J., Wu, J., Gao, Z., Sun, H., Yang, X., & Lo, H. K. (2019). Bus transit network design with uncertainties on the basis of a metro network: A two-step model framework. *Transportation Research Part B: Methodological*, *126*, 115–138. https://doi.org/10.1016/j.trb.2019.05.011

Liu, D., Durán Micco, J., Lu, G., Peng, Q., Ning, J., & Vansteenwegen, P. (2020). A Matheuristic Iterative Approach for Profit-Oriented Line Planning Applied to the Chinese High-Speed Railway Network. *Journal of Advanced Transportation*, *2020*. https://doi.org/10.1155/2020/4294195

Liu, Y., Bunker, J., & Ferreira, L. (2010). *Transit Users' Route-Choice Modelling in Transit Assignment: a Review*. http://eprints.qut.edu.au/

Luo, D., Cats, O., & van Lint, H. (2020). Can passenger flow distribution be estimated solely based on network properties in public transport systems? *Transportation*, *47*(6), 2757–2776. https://doi.org/10.1007/s11116-019-09990-w

Mahdavi Moghaddam, S. M. H., Rao, K. R., Tiwari, G., & Biyani, P. (2019). Simultaneous Bus Transit Route Network and Frequency Setting Search Algorithm. *Journal of Transportation Engineering, Part A: Systems*, *145*(4). https://doi.org/10.1061/jtepbs.0000229

Moeckel, R., Fussell, R., & Donnelly, R. (2015). Mode choice modeling for long-distance travel. *Transportation Letters*, *7*(1), 35–46. https://doi.org/10.1179/1942787514Y.0000000031

Moyano, A., & Dobruszkes, F. (2025). Privatising profits and socialising losses: The effects of liberalisation on the incumbent high-speed rail operator in Spain. *Research in Transportation Business and Management*, *60*. https://doi.org/10.1016/j.rtbm.2025.101317

Nisan, N., Roughgarden, T., Tardos, É., & Vazirani, V. V. (2007). *Algorithmic game theory*. Cambridge University Press.

Nussbaum, Y. (2010). *Multiple-source multiple-sink maximum flow in planar graphs*. http://arxiv.org/abs/1012.4767

ÖBB. (2024, March 22). *Hurra…die neuen Railjets sind da!* . https://www.unsereoebb.at/de/artikel/reiseblog/neue-railjets

Oliker, N., & Bekhor, S. (2020). A frequency based transit assignment model that considers online information and strict capacity constraints. *EURO Journal on Transportation and Logistics*, *9*(1). https://doi.org/10.1016/j.ejtl.2020.100005

Owais, M. (2026). Transit network design problem: a half century of methodological research. *Innovative Infrastructure Solutions*, *11*(1). https://doi.org/10.1007/s41062-025-02356-5

Praticò, F. G., & Fedele, R. (2023). Economic Sustainability of High–Speed and High–Capacity Railways. *Sustainability (Switzerland)*, *15*(1). https://doi.org/10.3390/su15010725

Puzis, R., Altshuler, Y., Elovici, Y., Bekhor, S., Shiftan, Y., & Pentland, A. (2013). Augmented betweenness centrality for environmentally aware traffic monitoring in transportation networks. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*, *17*(1), 91–105. https://doi.org/10.1080/15472450.2012.716663

Railway Gazette International. (2026, August 7). FS Group orders high speed trains for Trenitalia's London – Paris service. *Railway Gazette International* . https://www.railwaygazette.com/rolling-stock/2026/08/07/trenitalia-orders-high-speed-trains-for-london-paris-service/

Ranjbari, A., Shariat-Mohaymany, A., & Amiripour, S. M. M. (2011). Transit network design: The necessity of elastic demand consideration. *Applied Mechanics and Materials*, *97–98*, 1117–1122. https://doi.org/10.4028/www.scientific.net/AMM.97-98.1117

Raturi, V., Srinivasan, K., Narulkar, G., Chandrashekharaiah, A., & Gupta, A. (2013). Analyzing Inter-modal Competition between High Speed Rail and Conventional Transport Systems: A Game Theoretic Approach. *Procedia - Social and Behavioral Sciences*, *104*, 904–913. https://doi.org/10.1016/j.sbspro.2013.11.185

Raturi, V., & Verma, A. (2020). A game-theoretic approach to analyse inter-modal competition between high-speed rail and airlines in the Indian context. *Transportation Planning and Technology*, *43*(1), 20–47. https://doi.org/10.1080/03081060.2020.1701666

Rietveld, P. (2012). Barrier Effects of Borders: Implications for Border-Crossing Infrastructures. *EJTIR Issue*, *12*(2), 150–166. www.ejtir.tbm.tudelft.nl

Ristić, B., Stojadinović, N., & Trifunović, D. (2022). Conditions for effective on-track competition in the European passenger railway market: A yardstick for regulations. *Transport Policy*, *119*, 1–15. https://doi.org/10.1016/j.tranpol.2022.02.006

Schöbel, A. (2012). Line planning in public transportation: Models and methods. In *OR Spectrum* (Vol. 34, Number 3, pp. 491–510). https://doi.org/10.1007/s00291-011-0251-6

Šfiligoj, T., Peperko, A., Bajec, P., & Cats, O. (2025). Node importance corresponds to passenger demand in public transport networks. *Physica A: Statistical Mechanics and Its Applications*, *659*. https://doi.org/10.1016/j.physa.2025.130354

Shyr, O. F. Y., & Hung, M. F. (2010). Intermodal competition with high speed rail-a game theory approach. *Journal of Marine Science and Technology*, *18*(1), 32–40. https://doi.org/10.51400/2709-6998.1862

Siemens Mobility. (n.d.-a). *Expertise for the Eurotunnel*. Retrieved October 26, 2026, from https://www.mobility.siemens.com/global/en/portfolio/references/velaro-eurostar-e320.html

Siemens Mobility. (n.d.-b). *ICE 4, the high-speed train for Deutsche Bahn*. Retrieved October 26, 2026, from https://www.mobility.siemens.com/global/en/portfolio/rolling-stock/high-speed-and-intercity-trains/ice-4.html

Smith, A. S. J., & Nash, C. A. (2023). Will the latest British reforms to rail passenger service procurement work? *Research in Transportation Economics*, *100*. https://doi.org/10.1016/j.retrec.2023.101321

Špetík, O., Fitzová, H., Tomeš, Z., & Pařil, V. (2026). Rail competition and price dynamics in Czechia and Austria. *Research in Transportation Business and Management*, *66*. https://doi.org/10.1016/j.rtbm.2026.101634

Stadler Rail. (n.d.). *Grenzüberschreitend mit Highspeed: SMILE*. Retrieved October 26, 2026, from https://www.stadlerrail.com/de/loesungen/schienenfahrzeuge/vollbahnen-smile

Steer Davies Gleave. (2015). *Study on the Cost and Contribution of the Rail Sector European Commission Directorate General for Mobility and Transport Final Report*. www.steerdaviesgleave.com

Steer Davies Gleave. (2016). *Study on the prices and quality of rail passenger services*. www.steerdaviesgleave.com

Stoll, F., Nießen, N., & Kogel, B. (2024). Radical timetable innovations in long-distance railway passenger transport: How might these affect railway passenger demand? *Journal of Public Transportation*, *26*. https://doi.org/10.1016/j.jpubtr.2024.100090

Stone, J. (2026, August 25). Trains between Britain and Europe on track to run every 15 minutes . *Politico*. https://www.politico.eu/article/train-eurotunnel-britain-europe-every-fifteen-minutes/

Sun, X., Zheng, C., Wandelt, S., & Zhang, A. (2024). Airline competition: A comprehensive review of recent research. In *Journal of the Air Transport Research Society* (Vol. 2). Elsevier B.V. https://doi.org/10.1016/j.jatrs.2024.100013

Tomeš, Z., & Jandová, M. (2018). Open access passenger rail services in Central Europe. *Research in Transportation Economics*, *72*, 74–81. https://doi.org/10.1016/j.retrec.2018.10.002

Tomeš, Z., Kvizda, M., Jandová, M., & Rederer, V. (2016). Open access passenger rail competition in the Czech Republic. *Transport Policy*, *47*, 203–211. https://doi.org/10.1016/j.tranpol.2016.02.003

Tomeš, Z., Kvizda, M., Nigrin, T., & Seidenglanz, D. (2014). Competition in the railway passenger market in the Czech Republic. *Research in Transportation Economics*, *48*, 270–276. https://doi.org/10.1016/j.retrec.2014.09.052

UIC. (2018). *HIGH SPEED RAIL FAST TRACK TO SUSTAINABLE MOBILITY*.

Vaze, V., & Barnhart, C. (2012). Modeling airline frequency competition for airport congestion mitigation. *Transportation Science*, *46*(4), 512–535. https://doi.org/10.1287/trsc.1120.0412

Vigren, A. (2017). Competition in Swedish passenger railway: Entry in an open access market and its effect on prices. *Economics of Transportation*, *11–12*, 49–59. https://doi.org/10.1016/j.ecotra.2017.10.005

Vrtic, M. ;, & Axhausen, K. W. (2002). The impact of tilting trains in Switzerland A route choice model of regional-and long distance public transport trips. *Arbeitsberichte Verkehrs- Und Raumplanung*, (128). https://doi.org/10.3929/ethz-a-004403563

Wang, F., Wang, P., Bešinović, N., Pan, H., Huang, Y., & Dariano, A. (2022). *A multi-stage game-theoretical approach to study asymmetric competition-cooperation for the multi-operator railway network*. https://ssrn.com/abstract=5520885

Wardman, M. (2004). Public transport values of time. *Transport Policy*, *11*(4), 363–377. https://doi.org/10.1016/j.tranpol.2004.05.001

Wardman, M. (2012). Review and meta-analysis of U.K. time elasticities of travel demand. In *Transportation* (Vol. 39, Number 3, pp. 465–490). https://doi.org/10.1007/s11116-011-9369-2

Wardman, M. (2022). Meta-analysis of British time-related demand elasticity evidence: An update. *Transportation Research Part A: Policy and Practice*, *157*, 198–214. https://doi.org/10.1016/j.tra.2022.02.001

Whitaker, G., Enriquez, T., Thévenet, V., Mueller, J., & Cachero, G. (2026). *Advancing EU rail passenger rights*.

Wirth, F., & Weik, N. (2026). 30 years of tendering regional rail services in Germany – A data-based analysis of long-term effects and the impact of network characteristics on competition. *Transportation Research Part A: Policy and Practice*, *211*. https://doi.org/10.1016/j.tra.2026.105114

Yap, M. D., Nijënstein, S., & van Oort, N. (2018). Improving predictions of public transport usage during disturbances based on smart card data. *Transport Policy*, *61*, 84–95. https://doi.org/10.1016/j.tranpol.2017.10.010

A operator maps of baseline scenario

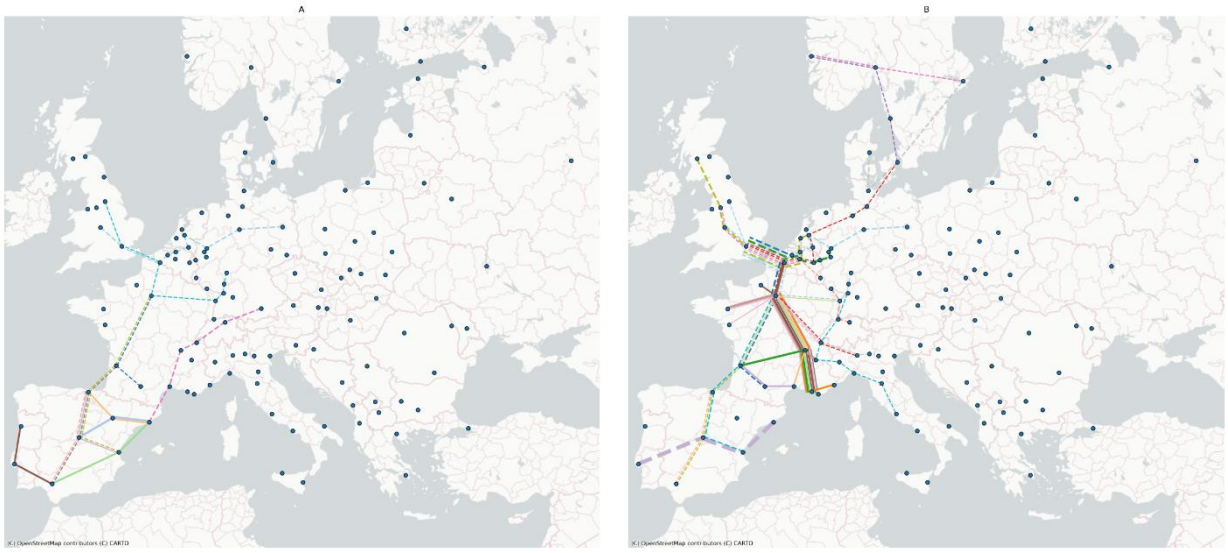


Figure 7.1: line maps of operators A & B in baseline scenario

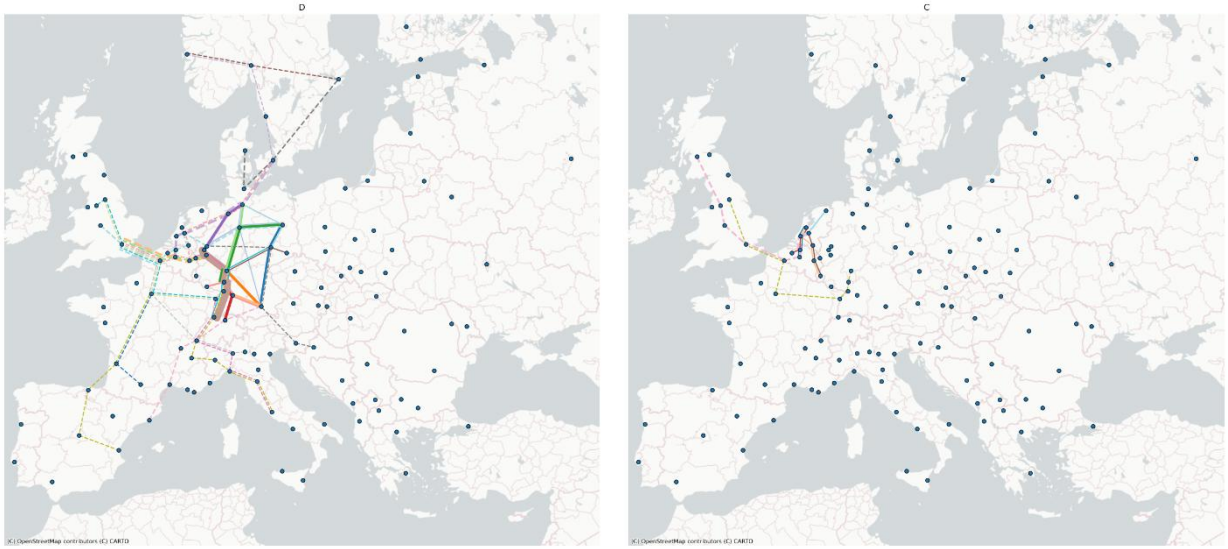


Figure 7.2: line maps of operators C & D in baseline scenario

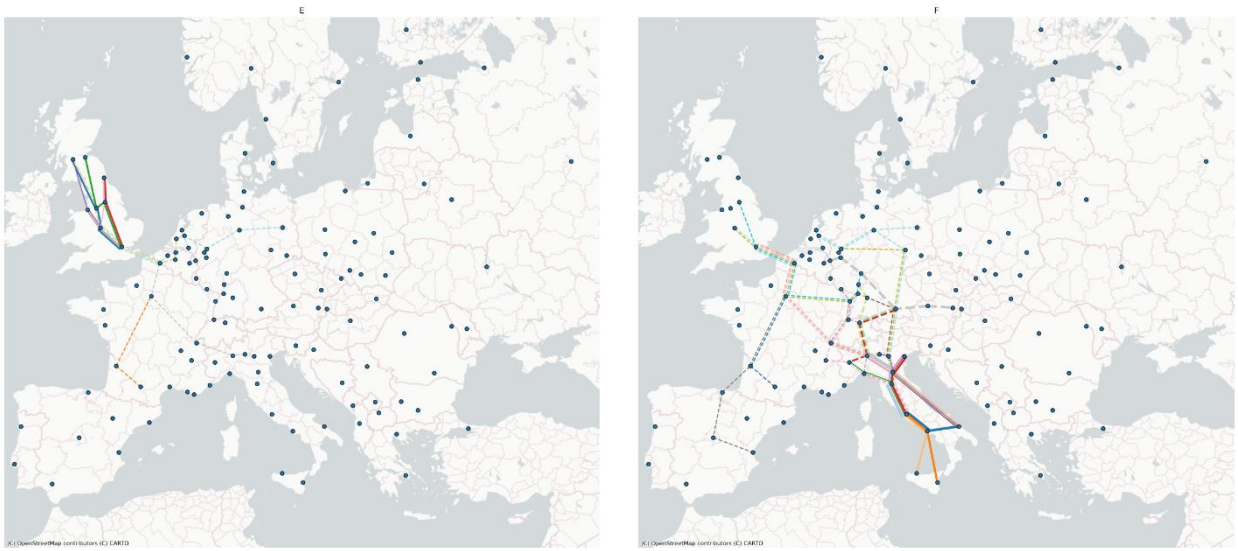


Figure 7.3: line maps of operators E & F in baseline scenario

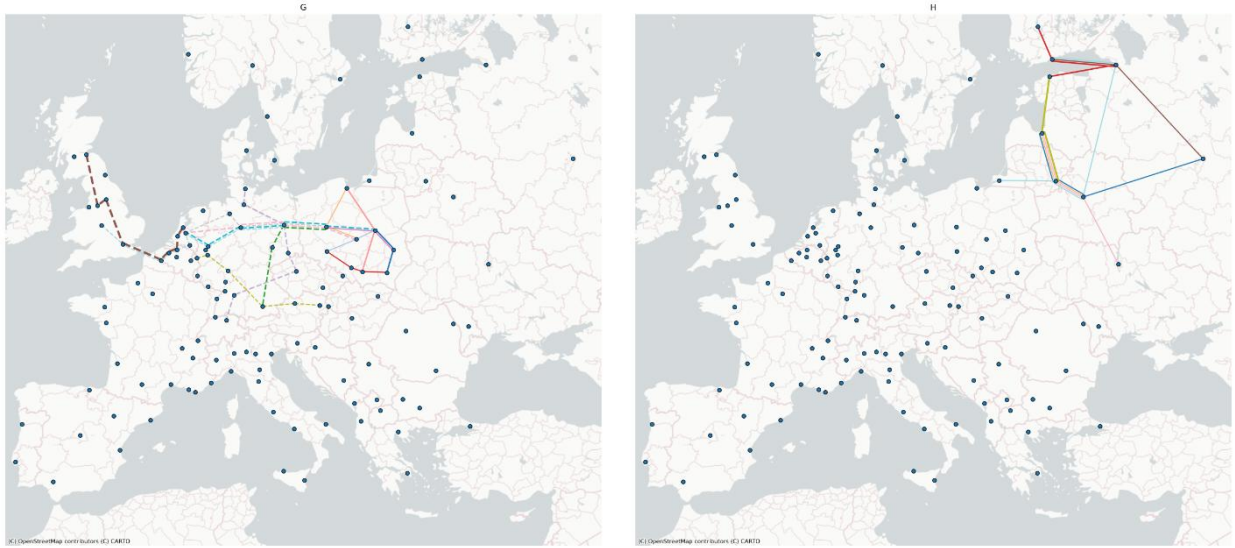


Figure 7.5: line maps of operators G & H in baseline scenario

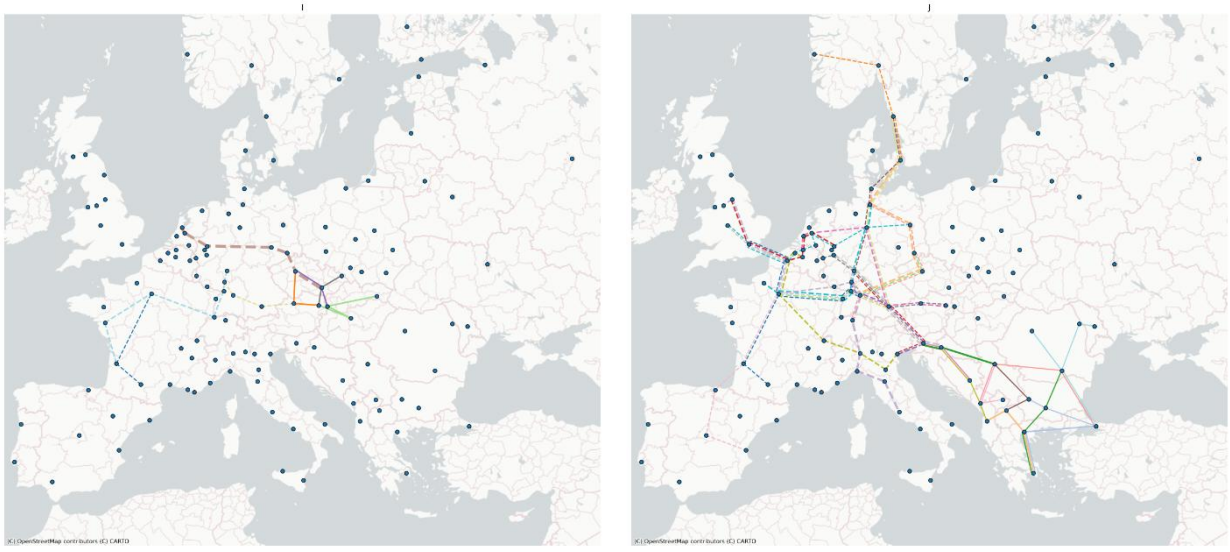


Figure 7.4: line maps of operators I & J in baseline scenario

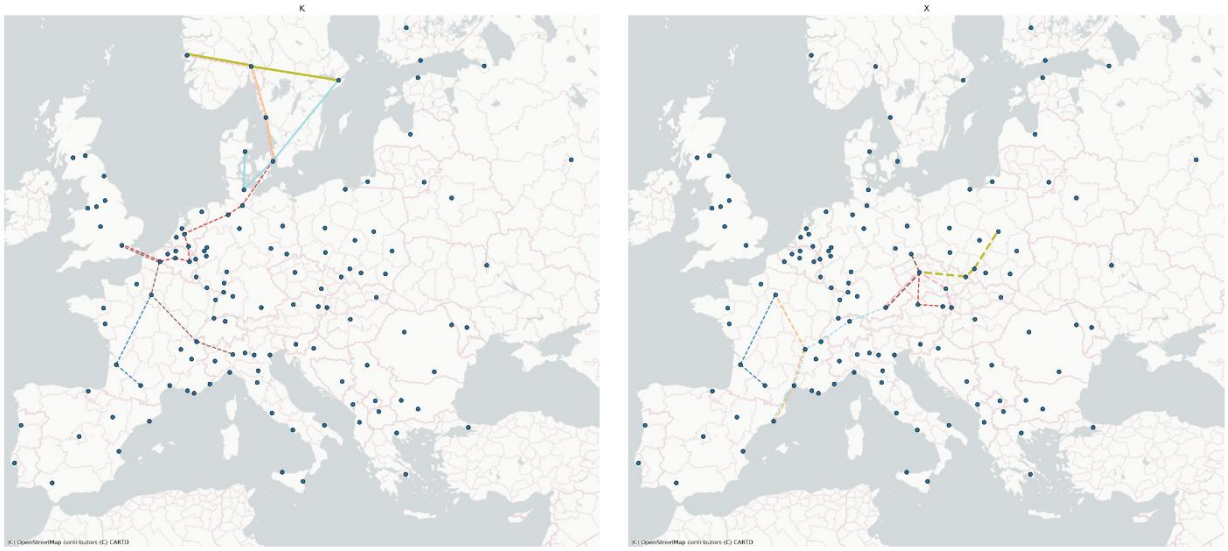


Figure 7.6: line maps of operators K & X in baseline scenario

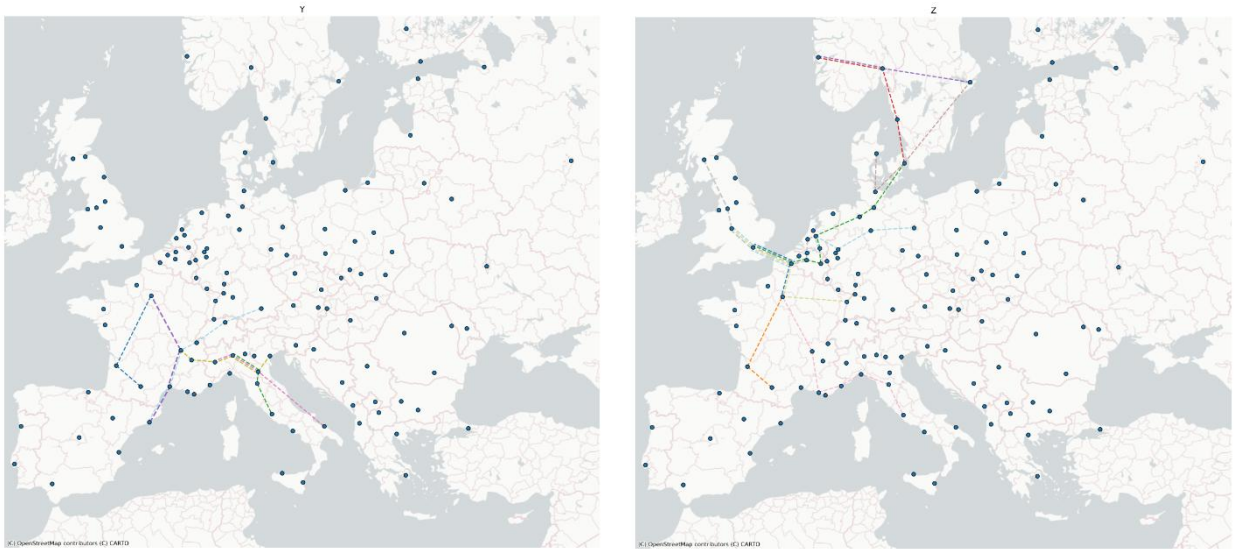


Figure 7.7: line maps of operators Y & Z in baseline scenario

B Full KPIs of sensitivity analyses

This section fully reports the KPI results of the sensitivity analyses presented in Subsection 5.2.3.

B.1 Entry cost sensitivity analysis

Table 7-1: Network KPIs for entry cost sensitivity analysis

	Value of k^{entry} (in €)						
Network KPIs	**10 000**	**25 000**	**50 000**	***70 000***	**90 000**	**120 000**	**150 000**
Number of active lines	198	223	187	***169***	148	127	115
Number of active services	612	616	271	***231***	207	172	160
Number of used edges	201	210	197	***196***	189	177	167
Number of reachable ODs	2 838	2 838	2 747	***2 747***	2 747	2 487	2 487
Train-kms (10^3 km)	1 655.57	1 533.67	724.71	***712.67***	695.40	707.86	714.13
Average stops per line	4.35	4.53	4.43	***4.31***	4.12	4.03	3.88
Average stops per service	4.66	4.81	4.82	***4.73***	4.59	4.56	4.40
Average line length (km)	782	851	816	***783.79***	743	727.32	710.02
Average service length (km)	855	992	882	***849.92***	804	811.89	803.23
Network Connectivity	0.554	0.579	0.543	***0.540***	0.521	0.488	0.460

Table 7-2: Network KPIs for entry cost sensitivity analysis

	Value of $\mathbf{k^{entry}}$ (in €)						
Passenger KPIs	**10 000**	**25 000**	**50 000**	**70 000**	**90 000**	**120 000**	**150 000**
Unserved passenger demand	164 159 (39.03%)	109 104 (25.72%)	102 347 (24.65%)	***98 599 (23.76%)***	109 665 (26.63%)	120 638 (29.60%)	130 199 (32.22%)
Served passenger demand	256 460 (60.97%)	315 167 (74.28%)	312 909 (75.35%)	***316 388 (76.24%)***	302 193 (73.37%)	286 985 (70.40%)	273 835 (67.78%)
Demand that can be served without any transfers	182 251 (71.06%)	226 705 (71.93%)	211 698 (67.65%)	***206 104 (65.14%)***	195 223 (64.60%)	184 487 (64.28%)	173 477 (63.35%)
Demand that can be served with 1 transfer	59 090 (23.04%)	74 391 (23.60%)	80 325 (25.67%)	***82 624 (26.11%)***	76 331 (25.26%)	78 190 (27.25%)	72 526 (26.49%)
Demand that can be served with 2 transfers	13 059 (5.09%)	12 478 (3.96%)	16 817 (5.37%)	***22 740 (7.19%)***	24 037 (7.95%)	18 329 (6.39%)	20 625 (7.53%)
Demand that can be served with 3+ transfers	2 059 (0.80%)	1 593 (0.51%)	4 070 (1.30%)	***4 919 (1.55%)***	6 602 (2.18%)	5 978 (2.08%)	7 207 (2.63%)
Passenger-kms (10^6 km)	154.97	192.91	192.88	***195.22***	186.17	181.20	174.06
Average travel distance per passenger	604.26	612.10	616.41	***617.03***	616.07	631.38	635.64
Average travel time per passenger (min)	198.74	200.15	204.09	***205.80***	206.22	210.03	212.53

It can be from Table 7-2 that the number of reachable ODs is up to the maximum of 2 838 for the scenarios of k^{entry} = 10 000 and k^{entry} = 20 000, signifying that the subnetwork of operator H in Northeastern Europe is connected to the rest of the network for both of these scenarios. This suggests that the connection to this area is slightly profitable, but that the additional entry costs deter the addition of those lines to the network.

B.2 Initial frequency sensitivity analysis

Table 7-3: Network KPIs for initial frequency sensitivity analysis

	Value of $f_{sl}^{initial}$					
Network KPIs	**3**	**6**	**9**	***12***	**15**	**18**
Number of active lines	143	144	159	***169***	166	167
Number of active services	222	232	240	***231***	230	231
Number of used edges	190	188	191	***196***	194	195
Number of reachable ODs	2 747	2747	2747	***2 747***	2 747	2 747
Train-kms (10^3 km)	693.27	730.30	698.07	***712.67***	710.54	692.60
Average stops per line	4.03	4.06	4.21	***4.31***	4.33	4.37
Average stops per service	4.60	4.51	4.78	***4.73***	4.74	4.83
Average line length (km)	756.64	753.66	753.51	***783.79***	780.23	781.99
Average service length (km)	842.52	863.31	858.85	***849.92***	847.01	850.32
Network Connectivity	0.523	0.518	0.526	***0.540***	0.534	0.537

Table 7-4: Passenger KPIs for initial frequency sensitivity analysis

	Value of $f_{sl}^{initial}$					
Passenger KPIs	**3**	**6**	**9**	***12***	**15**	**18**
Unserved passenger demand	114 507 (27.83%)	104 847 (26.41%)	107 389 (25.96%)	***98 599 (23.76%)***	104 773 (25.25%)	108 132 (26.04%)
Served passenger demand	296 967 (72.17%)	307 919 (74.60%)	306 242 (74.04%)	***316 388 (76.24%)***	310 129 (74.75%)	307 054 (73.96%)
Demand that can be served without any transfers	194 030 (65.34%)	198 544 (64.48%)	196 915 (64.30%)	***206 104 (65.14%)***	200 914 (64.78%)	202 592 (65.98%)
Demand that can be served with 1 transfer	75 439 (25.40%)	81 313 (26.41%)	79 993 (26.12%)	***82 624 (26.11%)***	82 671 (26.66%)	82 807 (26.97%)
Demand that can be served with 2 transfers	20 568 (6.93%)	21 843 (7.09%)	23 198 (7.58%)	***22 740 (7.19%)***	21 426 (6.91%)	17 608 (5.73%)
Demand that can be served with 3+ transfers	6 929 (2.33%)	6 219 (2.02%)	6 135 (2.00%)	***4 919 (1.55%)***	5 119 (1.65%)	4 048 (1.32%)
Passenger-kms (10^6 km)	183.94	190.61	188.04	***195.22***	190.61	187.87
Average travel distance per passenger	619.38	619.01	614.02	***617.03***	614.60	611.84
Average travel time per passenger (min)	206.95	207.14	205.54	***205.80***	205.22	203.46

C Line pool

Line nr.	Path	c_l^{line}
1	Glasgow - Manchester - Birmingham - London	611
2	London - Lille - Paris	456
3	Amsterdam - Rotterdam - Antwerpen - Gent - Lille - London	532
4	Aarhus - Kiel - Copenhagen	609
5	Paris - Bordeaux - Toulouse	753
6	Barcelona - Zaragoza - Madrid	570
7	Berlin - Leipzig - Munich	562
8	Edinburgh - Manchester - Leeds - London	659
9	London - Lille - Brussels - Antwerpen - Rotterdam	496
10	Bari - Napoli - Rome	448
11	Marseille - Lyon - Paris	706
12	Copenhagen - Gothenburg - Oslo	556
13	Milano - Bologna - Florence - Rome	557
14	Berlin - Hannover - Ruhrgebiet (Essen)	494
15	London - Birmingham - Manchester	299
16	London - Lille - Brussels - Liège - Eindhoven - Utrecht - Ruhrgebiet (Essen)	799
17	Munich - Hannover - Ruhrgebiet (Essen)	834
18	London - Lille - Gent - Antwerpen - Eindhoven - Utrecht	533
19	Berlin - Dresden - Prague - Stuttgart	748
20	Catania - Napoli - Rome	742
21	Hamburg - Hannover - Munich	733
22	Brussels - Lille - London	356
23	Berlin - Leipzig - Frankfurt Am Main	531
24	Palermo - Napoli - Rome	860
25	London - Leeds - Newcastle Upon Tyne	433
26	Birmingham - Liverpool - Glasgow	461
27	Barcelona - Montpellier - Lyon - Paris	1011
28	Barcelona - Zaragoza - Bilbao	560
29	Munich - Linz - Vienna	386
30	Nice - Marseille - Lyon - Paris	887
31	Barcelona - Valencia - Sevilla	917
32	London - Lille - Paris - Lyon	878
33	Bari - Bologna - Milano	800
34	Mannheim - Frankfurt Am Main - Munich	428
35	Berlin - Leipzig - Munich - Zürich	854
36	Frankfurt Am Main - Mannheim - Stuttgart	200
37	Grenoble - Geneva - Paris	619
38	Frankfurt Am Main - Hannover - Hamburg	456
39	Milano - Geneva - Paris	779
40	Berlin - Hannover - Frankfurt Am Main - Cologne	751
41	Hamburg - Bremen - Ruhrgebiet (Essen)	356
42	Frankfurt Am Main - Mannheim - Saarbrücken - Paris - Lille - London	1013
43	Hamburg - Hannover - Munich - Stuttgart	933
44	Rzeszow - Lublin - Warsaw	311
45	Helsinki - St. Petersburg - Tallinn - Riga	968
46	London - Lille - Paris - Basel - Zürich	1053
47	Rome - Florence - Genoa - Turin	615
48	Amsterdam - Utrecht - Ruhrgebiet (Essen)	206
49	Antwerpen - Gent - Lille - London	374
50	Milano - Bologna - Bari - Napoli	1039
51	Munich - Zürich - Basel - Paris	889
52	Milano - Zürich - Munich	546
53	Cologne - Frankfurt Am Main - Munich	529
54	Paris - Geneva - Zürich	744
55	Berlin - Hamburg - Copenhagen	558
56	Montpellier - Lyon - Paris	698
57	London - Lille - Paris - Strasbourg - Karlsruhe - Stuttgart	1052
58	Cologne - Aachen - Liège - Brussels - Lille - London	558
59	Amsterdam - Utrecht - Hannover - Berlin	622
60	Rome - Florence - Bologna - Venice	501
61	Berlin - Dresden - Prague - Brno - Vienna	622
62	Berlin - Leipzig - Ruhrgebiet (Essen) - Düsseldorf	624
63	Karlsruhe - Stuttgart - Munich	272
64	Eindhoven - Antwerpen - Brussels - Lille - London	485
65	Amsterdam - Utrecht - Hannover - Munich	962
66	Birmingham - Liverpool - Edinburgh	459
67	Berlin - Hannover - Frankfurt Am Main - Mannheim	650
68	Berlin - Hannover - Utrecht - Rotterdam - Antwerpen - Gent - Lille - London	1099
69	Liverpool - Birmingham - London	317
70	London - Lille - Paris - Basel - Zürich - Munich	1345
71	Amsterdam - Utrecht - Bremen - Hamburg - Copenhagen	756
72	Budapest - Ljubljana - Munich	788
73	Düsseldorf - Ruhrgebiet (Essen) - Leipzig - Munich	846
74	Amsterdam - Utrecht - Bremen - Hamburg	454
75	Bologna - Florence - Rome	362
76	Lyon - Geneva - Zürich	389
77	Bilbao - Madrid - Sevilla	843
78	Düsseldorf - Cologne - Aachen - Liège - Brussels - Lille - London	593
79	Munich - Ljubljana - Zagreb	494
80	Gent - Lille - London	321
81	Frankfurt Am Main - Mannheim - Saarbrücken - Paris	557
82	Barcelona - Montpellier - Lyon	589
83	Cologne - Frankfurt Am Main - Hannover - Hamburg	628
84	Hamburg - Bremen - Utrecht - Eindhoven - Antwerpen - Gent - Lille - London	950
85	Munich - Verona - Bologna - Florence - Rome	883
86	Barcelona - Montpellier - Lyon - Geneva - Milano	1013
87	Grenoble - Geneva - Paris - Lille - London	1075
88	Vienna - Linz - Zürich	686
89	Birmingham - Leeds - Newcastle Upon Tyne	322
90	Bilbao - Bordeaux - Paris	834
91	Paris - Lyon - Grenoble - Turin	732
92	London - Lille - Paris - Strasbourg	900
93	Ostrava - Katowice - Warsaw	351
94	Bordeaux - Lyon - Marseille	786
95	Bordeaux - Rouen - Lille - London	1080
96	Manchester - Leeds - London - Lille - Paris	805
97	Moscow - Minsk - Vilnius - Riga	1088
98	Amsterdam - Rotterdam - Antwerpen - Brussels - Lille - London - Birmingham	737
99	Geneva - Paris - Lille - London	947
100	Birmingham - London - Lille - Paris	629
101	Basel - Zürich - Munich	370
102	Kyiv - Minsk - Warsaw	1018
103	Paris - Luxembourg - Liège - Eindhoven - Utrecht	676
104	Amsterdam - Rotterdam - Antwerpen - Brussels	208
105	Bordeaux - Lyon - Grenoble	599
106	Berlin - Leipzig - Frankfurt Am Main - Mannheim - Saarbrücken - Paris	1088
107	Bremen - Hannover - Munich	714
108	London - Lille - Paris - Saarbrücken - Mannheim	942
109	Rotterdam - Utrecht - Ruhrgebiet (Essen)	219
110	Stuttgart - Prague - Brno - Vienna	750
111	Lyon - Bordeaux - Nantes	817
112	Hamburg - Hannover - Frankfurt Am Main - Mannheim	527
113	Hamburg - Hannover - Munich - Zürich	1025
114	Grenoble - Geneva - Zürich	381
115	Basel - Paris - Lille - London	975
116	Barcelona - Montpellier - Marseille - Grenoble	747
117	Rome - Florence - Bologna - Verona	493
118	Paris - Strasbourg - Karlsruhe - Stuttgart	596
119	Munich - Stuttgart - Karlsruhe - Strasbourg	352
120	Mannheim - Stuttgart - Zürich	325
121	Paris - Lyon - Marseille - Toulon	766
122	Munich - Zürich - Milano - Turin	675
123	Brussels - Luxembourg - Saarbrücken - Mannheim - Stuttgart - Munich	748
124	Copenhagen - Hamburg - Bremen - Utrecht - Eindhoven - Liège - Brussels - Lille - London	1349
125	Amsterdam - Rotterdam - Antwerpen - Gent - Lille - London - Leeds - Manchester	881
126	Bologna - Verona - Munich	521
127	Munich - Stuttgart - Mannheim - Saarbrücken	450
128	Amsterdam - Rotterdam - Eindhoven - Aachen - Cologne	329
129	Athens - Thessaloniki - Istanbul	986
130	Berlin - Dresden - Prague - Stuttgart - Karlsruhe	820
131	Barcelona - Zaragoza - Bordeaux	713
132	Berlin - Dresden - Prague - Stuttgart - Karlsruhe - Strasbourg	900
133	Bordeaux - Bilbao - Madrid	665
134	Madrid - Zaragoza - Bordeaux - Paris	1249
135	Copenhagen - Hamburg - Bremen - Ruhrgebiet (Essen)	658
136	Düsseldorf - Ruhrgebiet (Essen) - Bremen - Hamburg	386
137	Berlin - Hannover - Utrecht - Eindhoven - Antwerpen - Brussels	794
138	Munich - Verona - Venice	500
139	Berlin - Poznan - Warsaw	528
140	Nantes - Bordeaux - Toulouse	538
141	Bari - Bologna - Florence	713
142	London - Lille - Paris - Geneva - Milano	1235
143	Berlin - Hannover - Utrecht - Rotterdam	635
144	Frankfurt Am Main - Munich - Ljubljana - Vienna	1068
145	Prague - Linz - Vienna	390
146	Rome - Florence - Genoa - Milano - Zürich	843

147	Brescia - Milano - Genoa - Florence - Rome	672
148	Barcelona - Valencia - Madrid - Porto	1150
149	Strasbourg - Basel - Zürich	205
150	Genoa - Florence - Rome	461
151	London - Lille - Rouen - Paris - Saarbrücken	975
152	Warsaw - Lodz - Wroclaw	324
153	Bari - Bologna - Milano - Turin	929
154	Ljubljana - Venice - Bologna - Florence - Rome	719
155	Cologne - Aachen - Liège - Luxembourg - Paris	604
156	Amsterdam - Utrecht - Ruhrgebiet (Essen) - Düsseldorf	236
157	Groningen - Utrecht - Rotterdam - Antwerpen - Gent - Lille - London	684
158	Berlin - Hannover - Utrecht	585
159	Barcelona - Montpellier - Lyon - Geneva - Zürich	978
160	Munich - Hannover - Utrecht - Rotterdam	975
161	Napoli - Bari - Bologna - Milano - Turin	1168
162	Karlsruhe - Basel - Zürich	256
163	Riga - Tallinn - St. Petersburg	622
164	Frankfurt Am Main - Munich - Zürich - Milano	903
165	Liège - Brussels - Lille - London	443
166	Mannheim - Saarbrücken - Paris	486
167	Genoa - Milano - Geneva - Paris	907
168	Prague - Dresden - Leipzig - Ruhrgebiet (Essen)	659
169	Grenoble - Lyon - Toulouse	585
170	Hamburg - Bremen - Utrecht - Rotterdam	467
171	Paris - Basel - Karlsruhe - Stuttgart - Prague	1207
172	Minsk - Vilnius - Riga	435
173	Frankfurt Am Main - Mannheim - Karlsruhe - Strasbourg	215
174	Cologne - Frankfurt Am Main - Mannheim - Stuttgart	372
175	Florence - Bologna - Verona - Munich	629
176	Ruhrgebiet (Essen) - Leipzig - Munich - Linz - Vienna	1202
177	Dresden - Prague - Munich	481
178	Cologne - Frankfurt Am Main - Munich - Zürich	821
179	Munich - Hannover - Utrecht	925
180	Barcelona - Montpellier - Marseille	467
181	Barcelona - Montpellier - Marseille - Grenoble - Turin	960
182	Prague - Linz - Zürich	740
183	Frankfurt Am Main - Munich - Prague	704
184	Milano - Zürich - Stuttgart	450
185	Hamburg - Hannover - Frankfurt Am Main - Mannheim - Saarbrücken - Paris	1013
186	Düsseldorf - Cologne - Frankfurt Am Main	207
187	London - Lille - Brussels - Luxembourg	531
188	Saarbrücken - Mannheim - Stuttgart	250
189	Bari - Bologna - Verona - Brescia	800
190	Napoli - Bari - Bologna - Venice	983
191	London - Lille - Rouen	486
192	Karlsruhe - Strasbourg - Paris - Lille - London	980
193	Copenhagen - Hamburg - Bremen - Utrecht - Rotterdam	769
194	Madrid - Bilbao - Toulouse	765
195	Budapest - Ljubljana - Munich - Stuttgart	988
196	Amsterdam - Utrecht - Bremen - Hamburg - Kiel - Aarhus	789
197	Hamburg - Hannover - Frankfurt Am Main - Mannheim - Karlsruhe	591
198	Nice - Genoa - Florence - Rome	637
199	Basel - Karlsruhe - Stuttgart	250
200	London - Lille - Rouen - Bordeaux - Toulouse	1303
201	Hamburg - Hannover - Frankfurt Am Main - Mannheim - Karlsruhe - Strasbourg	671
202	Düsseldorf - Cologne - Aachen - Liège - Luxembourg - Paris	639
203	Basel - Zürich - Munich - Leipzig - Berlin	932
204	Amsterdam - Rotterdam - Eindhoven - Liège	275
205	Birmingham - London - Lille - Gent - Antwerpen - Rotterdam	637
206	Lyon - Marseille - Nice	465
207	Copenhagen - Hamburg - Berlin - Poznan - Gdansk	1084
208	Amsterdam - Rotterdam - Antwerpen - Brussels - Lille	309
209	Barcelona - Montpellier - Marseille - Nice	648
210	Manchester - Birmingham - London - Lille - Gent - Antwerpen - Rotterdam	763
211	Kiel - Hamburg - Hannover - Munich	824
212	Paris - Geneva - Milano - Brescia - Verona	926
213	Berlin - Dresden - Prague - Brno	498
214	Berlin - Leipzig - Frankfurt Am Main - Mannheim - Saarbrücken	723
215	Copenhagen - Hamburg - Hannover - Frankfurt Am Main	758
216	Copenhagen - Hamburg - Berlin - Dresden - Prague	868
217	Budapest - Vienna - Linz - Zürich	906
218	Bilbao - Madrid - Valencia	683
219	Frankfurt Am Main - Cologne - Aachen - Eindhoven - Rotterdam	433
220	Paris - Geneva - Milano - Bologna - Venice	1113
221	Porto - Lisbon - Sevilla	704
222	Brussels - Luxembourg - Strasbourg - Basel - Zürich	611
223	Saarbrücken - Strasbourg - Basel - Zürich	312
224	Bologna - Bari - Napoli	844
225	Barcelona - Montpellier - Lyon - Geneva	725
226	London - Lille - Rouen - Nantes	837
227	Antwerpen - Eindhoven - Utrecht - Ruhrgebiet (Essen)	328
228	Istanbul - Plovdiv - Sofia	512
229	Luxembourg - Strasbourg - Karlsruhe - Stuttgart - Munich	583
230	Brussels - Liège - Aachen - Cologne	202
231	Hamburg - Bremen - Utrecht	417
232	Düsseldorf - Cologne - Frankfurt Am Main - Munich - Zürich	856
233	Cologne - Aachen - Eindhoven - Rotterdam	261
234	Bari - Bologna - Venice	744
235	Bari - Bologna - Verona	736
236	Krakow - Katowice - Lodz	260
237	Basel - Karlsruhe - Mannheim - Frankfurt Am Main	313
238	Aachen - Liège - Brussels - Lille - London	493
239	Bergen - Oslo - Gothenburg - Copenhagen	971
240	Glasgow - Manchester - Leeds	376
241	Bremen - Utrecht - Eindhoven - Antwerpen - Gent - Lille - London	836
242	Grenoble - Lyon - Bordeaux - Nantes	914
243	Nice - Genoa - Milano - Zürich	558
244	Lyon - Paris - Rennes	739
245	Amsterdam - Utrecht - Hannover - Frankfurt Am Main - Mannheim	756
246	London - Lille - Paris - Lyon - Marseille	1162
247	Bologna - Milano - Geneva - Paris	974
248	Vienna - Brno - Ostrava - Krakow - Warsaw	699
249	Budapest - Ljubljana - Munich - Frankfurt Am Main	1145
250	Hannover - Utrecht - Eindhoven - Antwerpen - Brussels - Lille - London	892
251	Liège - Aachen - Cologne - Frankfurt Am Main - Munich	644
252	Brescia - Milano - Geneva - Paris	862
253	Bremen - Hannover - Frankfurt Am Main	437
254	Hamburg - Hannover - Munich - Linz - Vienna	1119
255	Aachen - Cologne - Frankfurt Am Main - Leipzig - Berlin	768
256	Amsterdam - Utrecht - Hannover - Munich - Verona - Brescia - Milano	1499
257	Barcelona - Valencia - Madrid - Lisbon	1209
258	Bratislava - Brno - Prague - Munich	652
259	Mannheim - Stuttgart - Prague - Brno - Vienna	879
260	Copenhagen - Hamburg - Bremen - Utrecht	719
261	Eindhoven - Liège - Luxembourg - Paris	596
262	Marseille - Montpellier - Toulouse	374
263	Marseille - Lyon - Bordeaux - Nantes	1101
264	Berlin - Hannover - Utrecht - Eindhoven	665
265	Bremen - Ruhrgebiet (Essen) - Düsseldorf - Cologne	307
266	Liverpool - Birmingham - London - Lille - Paris	773
267	Bremen - Hannover - Munich - Stuttgart	914
268	Rouen - Bordeaux - Toulouse	817
269	Napoli - Bari - Bologna - Verona	975
270	Brussels - Antwerpen - Eindhoven - Utrecht - Bremen - Hamburg	626
271	Grenoble - Marseille - Nice	461
272	Antwerpen - Liège - Aachen - Cologne - Frankfurt Am Main - Munich	752
273	Marseille - Nice - Genoa - Florence - Rome	818
274	Berlin - Hannover - Utrecht - Eindhoven - Liège	772
275	Amsterdam - Rotterdam - Antwerpen - Liège - Luxembourg - Strasbourg - Basel	742
276	Berlin - Hamburg - Copenhagen - Stockholm	1152
277	Frankfurt Am Main - Mannheim - Saarbrücken - Luxembourg	315
278	Basel - Karlsruhe - Mannheim	242
279	Budapest - Vienna - Venice - Bologna - Milano	1104
280	Brussels - Luxembourg - Strasbourg - Karlsruhe - Stuttgart	558
281	Bordeaux - Rouen - Lille	825
282	Copenhagen - Hamburg - Hannover - Munich	1035
283	Brescia - Verona - Bologna - Bari - Napoli	1039
284	Athens - Thessaloniki - Sofia	720
285	Antwerpen - Rotterdam - Utrecht - Hannover - Berlin	725
286	Düsseldorf - Ruhrgebiet (Essen) - Utrecht - Rotterdam	249
287	Prague - Ostrava - Katowice - Warsaw	692
288	Brussels - Liège - Aachen - Cologne - Düsseldorf	237
289	Strasbourg - Basel - Zürich - Linz - Vienna	891
290	Milano - Bologna - Venice - Vienna	884
291	Amsterdam - Rotterdam - Antwerpen - Gent - Lille - London - Birmingham - Liverpool	849
292	Amsterdam - Utrecht - Bremen	340
293	Leeds - London - Lille - Paris	741
294	Mannheim - Stuttgart - Prague	567
295	Eindhoven - Aachen - Cologne - Frankfurt Am Main - Munich	690
296	Berlin - Hannover - Utrecht - Eindhoven - Antwerpen - Brussels - Lille	895
297	Copenhagen - Hamburg - Berlin - Dresden - Prague - Stuttgart	1306

298	Lille - Rouen - Bordeaux - Toulouse	1048
299	Cologne - Düsseldorf - Ruhrgebiet (Essen) - Utrecht	234
300	Marseille - Grenoble - Geneva - Zürich	661
301	Riga - Vilnius - Warsaw	690
302	Lyon - Grenoble - Turin - Genoa - Florence - Rome	925
303	Brussels - Lille - London - Leeds - Manchester	705
304	Aachen - Cologne - Frankfurt Am Main - Munich	594
305	Lille - Gent - Antwerpen - Rotterdam	209
306	Amsterdam - Rotterdam - Antwerpen - Gent - Lille - London - Leeds	817
307	Brussels - Luxembourg - Saarbrücken - Mannheim - Frankfurt Am Main	490
308	Copenhagen - Hamburg - Hannover - Frankfurt Am Main - Mannheim - Saarbrücken - Paris	1315
309	Birmingham - London - Lille - Brussels - Antwerpen - Eindhoven - Utrecht	738
310	Brno - Prague - Munich	535
311	Bologna - Milano - Zürich	449
312	Bucharest - Budapest - Vienna	980
313	Manchester - Birmingham - London - Lille - Brussels - Liège - Eindhoven - Utrecht	929
314	Lisbon - Sevilla - Valencia	1017
315	Milano - Zürich - Linz - Prague	994
316	Kiel - Hamburg - Berlin - Dresden - Prague - Stuttgart	1095
317	Belgrade - Zagreb - Vienna	697
318	Catania - Napoli - Rome - Florence	996
319	Lille - Rouen - Paris - Basel - Zürich - Munich	1244
320	Amsterdam - Rotterdam - Eindhoven - Liège - Luxembourg - Paris - Lyon	1186
321	Basel - Zürich - Linz - Vienna	764
322	Karlsruhe - Basel - Paris	697
323	Bordeaux - Toulouse - Montpellier	443
324	Marseille - Lyon - Paris - Rouen	830
325	Tallinn - St. Petersburg - Helsinki - Tampere	844
326	Cologne - Frankfurt Am Main - Mannheim	243
327	Florence - Genoa - Milano - Geneva - Paris	1114
328	Mannheim - Stuttgart - Zürich - Milano	579
329	Grenoble - Turin - Genoa - Florence - Rome	828
330	Bordeaux - Lyon - Geneva	638
331	London - Lille - Rouen - Rennes	769
332	Berlin - Dresden - Prague - Brno - Bratislava	615
333	Karlsruhe - Stuttgart - Zürich - Linz - Vienna	954
334	Stuttgart - Zürich - Milano - Turin	579
335	Athens - Thessaloniki - Skopje - Tirana	922
336	Hamburg - Hannover - Frankfurt Am Main - Mannheim - Saarbrücken	648
337	Bordeaux - Lyon - Marseille - Nice	967
338	Geneva - Grenoble - Marseille	408
339	Geneva - Grenoble - Marseille - Nice	589
340	Frankfurt Am Main - Hannover - Hamburg - Kiel	547
341	Florence - Genoa - Milano - Zürich	589
342	Manchester - Leeds - London - Lille - Gent - Antwerpen - Rotterdam - Utrecht - Ruhrgebiet (Essen)	1032
343	Amsterdam - Utrecht - Hannover	364
344	Belgrade - Zagreb - Ljubljana - Munich	855
345	Cologne - Frankfurt Am Main - Munich - Ljubljana - Vienna	1240
346	Lille - Paris - Geneva - Zürich	945
347	Dresden - Leipzig - Ruhrgebiet (Essen)	525
348	Aarhus - Kiel - Copenhagen - Gothenburg - Oslo	1165
349	Rome - Florence - Bologna - Venice - Vienna	1051
350	Amsterdam - Rotterdam - Eindhoven - Liège - Luxembourg - Strasbourg	624
351	Berlin - Leipzig - Munich - Verona - Brescia - Milano	1099
352	Rennes - Nantes - Bordeaux - Toulouse	634
353	Brussels - Antwerpen - Rotterdam - Utrecht - Bremen - Hamburg - Copenhagen	909
354	Amsterdam - Rotterdam - Eindhoven - Liège - Luxembourg	393
355	Hannover - Munich - Zürich	890
356	Prague - Dresden - Leipzig - Hannover - Utrecht - Rotterdam	850
357	Liège - Antwerpen - Rotterdam	198
358	Dresden - Leipzig - Frankfurt Am Main	462
359	Antwerpen - Liège - Aachen - Cologne	223
360	Lille - Paris - Lyon - Marseille	907
361	Amsterdam - Rotterdam - Antwerpen - Brussels - Luxembourg - Strasbourg - Karlsruhe	694
362	Cologne - Frankfurt Am Main - Munich - Prague	876
363	Mannheim - Saarbrücken - Luxembourg - Liège - Eindhoven - Rotterdam	569
364	Stuttgart - Munich - Verona - Venice	700
365	Brescia - Verona - Munich	454
366	Lille - London - Birmingham - Manchester	554
367	Bologna - Bari - Napoli - Catania	1377
368	Cologne - Düsseldorf - Ruhrgebiet (Essen) - Bremen - Hamburg - Copenhagen	723
369	Aarhus - Kiel - Hamburg - Bremen - Utrecht - Rotterdam	802
370	Geneva - Zürich - Munich	545
371	Cologne - Frankfurt Am Main - Munich - Verona - Brescia - Milano	1066
372	Aachen - Eindhoven - Rotterdam - Amsterdam	264
373	Rome - Florence - Genoa - Milano - Zürich - Stuttgart	1039
374	Bremen - Ruhrgebiet (Essen) - Düsseldorf	272
375	Leipzig - Munich - Stuttgart	592
376	Frankfurt Am Main - Munich - Verona - Brescia - Milano - Turin	1023
377	Lille - Rouen - Paris - Geneva - Milano	1134
378	Barcelona - Montpellier - Lyon - Geneva - Milano - Brescia	1096
379	Bologna - Milano - Zürich - Stuttgart	645
380	Lille - Gent - Antwerpen - Eindhoven - Utrecht - Ruhrgebiet (Essen)	447
381	Amsterdam - Rotterdam - Antwerpen - Brussels - Luxembourg - Saarbrücken	506
382	Helsinki - St. Petersburg - Moscow	987
383	Basel - Strasbourg - Saarbrücken	234
384	Liège - Eindhoven - Utrecht	187
385	Copenhagen - Hamburg - Bremen - Groningen	578
386	Antwerpen - Liège - Luxembourg - Strasbourg - Basel - Zürich	662
387	Dresden - Prague - Stuttgart	572
388	Budapest - Ljubljana - Venice - Bologna - Florence - Rome	1138
389	Frankfurt Am Main - Cologne - Aachen - Liège - Brussels - Lille	475
390	Kiel - Hamburg - Hannover - Ruhrgebiet (Essen)	462
391	Budapest - Ljubljana - Munich - Stuttgart - Mannheim	1117
392	Barcelona - Montpellier - Marseille - Nice - Genoa - Florence	1031
393	Frankfurt Am Main - Mannheim - Karlsruhe - Basel - Geneva - Grenoble	671
394	Florence - Genoa - Milano - Zürich - Stuttgart	785
395	Stuttgart - Munich - Ljubljana - Zagreb	694
396	Lodz - Katowice - Ostrava	270
397	Brussels - Luxembourg - Paris - Lyon	968
398	Hamburg - Bremen - Utrecht - Eindhoven - Liège	604
399	Milano - Geneva - Basel - Strasbourg - Saarbrücken	752
400	Athens - Thessaloniki - Plovdiv - Bucharest	1222
401	Brussels - Luxembourg - Strasbourg - Karlsruhe - Stuttgart - Prague	996
402	Turin - Milano - Zürich	383
403	Frankfurt Am Main - Munich - Ljubljana - Zagreb	851
404	Bari - Bologna - Milano - Genoa	928
405	Kyiv - Minsk - Vilnius - Riga	956
406	Lille - Gent - Antwerpen - Eindhoven - Utrecht	278
407	Frankfurt Am Main - Cologne - Aachen - Liège	287
408	Bilbao - Porto - Lisbon	901
409	Glasgow - Manchester - Leeds - London - Lille - Paris	1117
410	Cluj-Napoca - Budapest - Ljubljana - Munich	1213
411	Munich - Verona - Brescia - Milano - Genoa - Nice	841
412	Milano - Geneva - Basel - Strasbourg	645
413	Newcastle Upon Tyne - Leeds - London - Lille - Rouen - Paris	1043
414	Liverpool - Birmingham - London - Lille - Brussels - Antwerpen - Rotterdam	813
415	Brno - Prague - Linz - Zürich	928
416	Istanbul - Thessaloniki - Skopje	739
417	Belgrade - Zagreb - Ljubljana	486
418	Copenhagen - Hamburg - Hannover - Ruhrgebiet (Essen) - Düsseldorf	703
419	Bremen - Hannover - Munich - Zürich	1006
420	Katowice - Krakow - Rzeszow	232
421	Basel - Geneva - Grenoble	358
422	Paris - Basel - Zürich - Linz - Vienna	1283
423	Budapest - Belgrade - Sofia	701
424	Eindhoven - Utrecht - Bremen - Hamburg	497
425	Genoa - Florence - Rome - Napoli	670
426	Ruhrgebiet (Essen) - Leipzig - Munich - Verona - Brescia - Milano - Turin	1482
427	Hannover - Frankfurt Am Main - Mannheim - Saarbrücken - Paris	878
428	Kiel - Hamburg - Bremen - Groningen - Utrecht - Eindhoven - Antwerpen - Gent - Lille - London	1070
429	Lodz - Warsaw - Lublin - Rzeszow	429
430	Amsterdam - Rotterdam - Eindhoven - Liège - Luxembourg - Paris - Lyon - Grenoble	1283
431	Gdansk - Poznan - Lodz	468
432	Munich - Leipzig - Berlin - Poznan	807
433	Prague - Stuttgart - Mannheim - Saarbrücken	688
434	Düsseldorf - Ruhrgebiet (Essen) - Hannover	266
435	Leeds - London - Lille - Brussels - Antwerpen - Rotterdam	781
436	Dresden - Prague - Stuttgart - Karlsruhe - Strasbourg - Paris	1168
437	Florence - Rome - Napoli - Palermo	1114
438	Edinburgh - Newcastle Upon Tyne - Leeds	324

439	Aachen - Eindhoven - Utrecht - Bremen - Hamburg	593
440	Copenhagen - Hamburg - Bremen - Groningen - Utrecht - Rotterdam - Antwerpen - Gent - Lille	1007
441	Antwerpen - Eindhoven - Utrecht - Bremen - Hamburg	576
442	Eindhoven - Liège - Luxembourg - Strasbourg - Basel - Zürich	661
443	Nice - Marseille - Montpellier - Toulouse	555
444	Munich - Prague - Ostrava - Krakow - Warsaw	1108
445	Düsseldorf - Cologne - Frankfurt Am Main - Mannheim	278
446	Munich - Verona - Bologna - Bari - Napoli	1365
447	Bordeaux - Bilbao - Porto - Lisbon	1205
448	Grenoble - Lyon - Paris - Rennes	836
449	Genoa - Milano - Brescia - Verona - Munich	665
450	Barcelona - Montpellier - Lyon - Geneva - Milano - Bologna	1208
451	Basel - Karlsruhe - Mannheim - Frankfurt Am Main - Cologne	485
452	Marseille - Grenoble - Geneva - Zürich - Linz - Munich	1397
453	Düsseldorf - Ruhrgebiet (Essen) - Hannover - Munich - Linz - Vienna	1250
454	Aarhus - Kiel - Hamburg - Bremen - Groningen - Utrecht	781
455	Hannover - Frankfurt Am Main - Mannheim	392
456	Lyon - Paris - Luxembourg - Liège - Eindhoven - Rotterdam	1118
457	Kyiv - Lublin - Warsaw - Lodz	835
458	Krakow - Ostrava - Prague - Munich	839
459	Basel - Geneva - Lyon	366
460	Barcelona - Montpellier - Marseille - Nice - Genoa - Florence - Rome	1285
461	Madrid - Zaragoza - Bordeaux - Nantes	1034
462	Barcelona - Montpellier - Lyon - Geneva - Milano - Brescia - Verona	1160
463	Milano - Geneva - Paris - Luxembourg - Brussels - Antwerpen - Rotterdam	1465
464	Zagreb - Ljubljana - Linz - Zürich	1016
465	Prague - Dresden - Leipzig - Hannover - Utrecht	800
466	Barcelona - Zaragoza - Bordeaux - Nantes	1028
467	Amsterdam - Rotterdam - Antwerpen - Gent - Lille - London - Leeds - Newcastle Upon Tyne	965
468	Amsterdam - Utrecht - Bremen - Hamburg - Kiel	545
469	Antwerpen - Liège - Luxembourg - Strasbourg - Karlsruhe - Stuttgart	609
470	Antwerpen - Brussels - Lille - London - Birmingham - Manchester	705
471	Copenhagen - Kiel - Hamburg - Hannover - Frankfurt Am Main - Mannheim	983
472	Düsseldorf - Ruhrgebiet (Essen) - Leipzig - Dresden - Prague	689
473	Karlsruhe - Stuttgart - Prague	510
474	Brno - Prague - Stuttgart	626
475	Madrid - Bilbao - Toulouse - Montpellier - Marseille	1139
476	Karlsruhe - Basel - Geneva - Milano	696
477	Amsterdam - Rotterdam - Antwerpen - Gent - Lille - London - Birmingham - Liverpool - Glasgow	1166
478	Amsterdam - Rotterdam - Eindhoven - Liège - Luxembourg - Paris - Bordeaux	1294
479	Basel - Strasbourg - Luxembourg - Liège - Eindhoven - Rotterdam	683
480	Eindhoven - Aachen - Cologne - Frankfurt Am Main	333
481	Düsseldorf - Cologne - Aachen - Liège - Luxembourg	268
482	Luxembourg - Strasbourg - Basel - Zürich	436
483	Copenhagen - Hamburg - Berlin - Poznan - Warsaw	1086
484	Lyon - Geneva - Zürich - Stuttgart	585
485	Birmingham - London - Lille - Brussels	529
486	Budapest - Zagreb - Sarajevo	684
487	Ruhrgebiet (Essen) - Hannover - Berlin - Poznan - Warsaw	1022
488	Leipzig - Munich - Zürich	684
489	Brussels - Luxembourg - Saarbrücken - Mannheim	419
490	Lille - Rouen - Nantes	582
491	Munich - Prague - Ostrava	688
492	Prague - Stuttgart - Karlsruhe - Strasbourg	590
493	Luxembourg - Saarbrücken - Mannheim	244
494	Bergen - Oslo - Stockholm	892
495	Leipzig - Munich - Zürich - Basel - Paris	1281
496	Bremen - Groningen - Utrecht - Rotterdam	382
497	Brno - Prague - Dresden - Berlin - Hamburg	754
498	Berlin - Leipzig - Frankfurt Am Main - Mannheim - Saarbrücken - Luxembourg	846
499	Hamburg - Copenhagen - Stockholm	896
500	Lyon - Toulouse - Bilbao - Madrid	1253
501	Copenhagen - Kiel - Hamburg - Berlin - Dresden	888
502	Lille - Paris - Basel - Karlsruhe - Stuttgart	970
503	Montpellier - Toulouse - Bordeaux - Nantes	758
504	Cologne - Aachen - Liège - Luxembourg - Saarbrücken	356
505	Geneva - Milano - Bologna - Florence - Rome	845
506	Saarbrücken - Mannheim - Stuttgart - Prague - Brno - Vienna	1000
507	Antwerpen - Eindhoven - Aachen - Cologne - Frankfurt Am Main	412
508	Dresden - Prague - Stuttgart - Zürich	768
509	Bordeaux - Lyon - Marseille - Toulon	846
510	Bologna - Verona - Munich - Frankfurt Am Main	878
511	Cologne - Aachen - Liège - Luxembourg - Paris - Lyon	1026
512	Liège - Luxembourg - Paris	489
513	Bordeaux - Nantes - Rennes	411
514	Barcelona - Montpellier - Marseille - Toulon	527
515	Berlin - Poznan - Lodz	432
516	Basel - Karlsruhe - Mannheim - Frankfurt Am Main - Cologne - Düsseldorf	520
517	Groningen - Utrecht - Eindhoven - Antwerpen - Brussels - Luxembourg - Paris	925
518	Rzeszow - Krakow - Katowice - Wroclaw	415
519	Ostrava - Krakow - Rzeszow	311
520	Amsterdam - Rotterdam - Antwerpen - Gent	211
521	Barcelona - Montpellier - Marseille - Nice - Genoa	824
522	Basel - Geneva - Grenoble - Turin - Genoa - Florence - Rome	1186
523	Budapest - Ljubljana - Munich - Stuttgart - Karlsruhe	1060
524	Porto - Madrid - Valencia	831
525	Bordeaux - Lyon - Geneva - Zürich	891
526	Basel - Zürich - Linz - Vienna - Budapest	984
527	Rotterdam - Antwerpen - Brussels - Luxembourg - Strasbourg	546
528	Berlin - Leipzig - Munich - Linz	780
529	Copenhagen - Kiel - Hamburg - Hannover - Leipzig	829
530	Eindhoven - Liège - Luxembourg - Saarbrücken - Mannheim - Stuttgart	598
531	Bratislava - Brno - Prague - Stuttgart	743
532	Brno - Ostrava - Katowice - Wroclaw - Dresden - Leipzig - Ruhrgebiet (Essen)	1191
533	Bordeaux - Paris - Luxembourg - Brussels	1076
534	Basel - Geneva - Grenoble - Marseille - Nice	819
535	Berlin - Hannover - Bremen - Groningen	536
536	Brno - Prague - Munich - Frankfurt Am Main	892
537	Aachen - Liège - Luxembourg - Paris	539
538	Liège - Luxembourg - Strasbourg - Basel - Zürich	554
539	Marseille - Lyon - Paris - Rennes	1023
540	Milano - Brescia - Verona - Munich - Hannover - Utrecht	1462
541	Antwerpen - Eindhoven - Utrecht - Bremen - Hamburg - Copenhagen	878
542	Brussels - Luxembourg - Paris - Lyon - Grenoble	1065
543	Brno - Bratislava - Budapest	299
544	Edinburgh - Newcastle Upon Tyne - Leeds - London - Lille - Paris	1065
545	Sofia - Cluj-Napoca - Budapest - Vienna	1227
546	Hamburg - Hannover - Ruhrgebiet (Essen) - Düsseldorf - Cologne - Aachen - Liège - Brussels - Lille	739
547	Geneva - Paris - Nantes	840
548	Lodz - Katowice - Ostrava - Brno - Vienna	549
549	Eindhoven - Antwerpen - Gent - Lille - London - Leeds - Manchester	802
550	Liège - Luxembourg - Saarbrücken - Mannheim - Stuttgart	491
551	Geneva - Lyon - Toulouse	624
552	Copenhagen - Hamburg - Bremen - Utrecht - Eindhoven	799
553	Amsterdam - Utrecht - Groningen - Bremen - Hamburg - Kiel - Copenhagen - Gothenburg	1226
554	Bordeaux - Bilbao - Porto	920
555	Brussels - Lille - London - Leeds	641
556	Cologne - Frankfurt Am Main - Leipzig - Dresden	634
557	Luxembourg - Brussels - Antwerpen - Rotterdam	315
558	Grenoble - Geneva - Zürich - Stuttgart	577
559	Athens - Thessaloniki - Sofia - Belgrade	1076
560	Frankfurt Am Main - Mannheim - Karlsruhe - Basel - Geneva	543
561	Barcelona - Montpellier - Lyon - Geneva - Zürich - Stuttgart	1174
562	Grenoble - Lyon - Toulouse - Bilbao - Madrid	1350
563	Bratislava - Budapest - Zagreb	498
564	Kyiv - Rzeszow - Krakow	807
565	Bremen - Hamburg - Copenhagen	416
566	Berlin - Hannover - Utrecht - Rotterdam - Antwerpen - Gent	778
567	Gent - Antwerpen - Eindhoven - Utrecht - Ruhrgebiet (Essen)	381
568	Brussels - Lille - London - Birmingham - Liverpool	673
569	Brussels - Luxembourg - Strasbourg - Basel - Zürich - Linz - Vienna	1297
570	Genoa - Turin - Grenoble - Lyon	464
571	Frankfurt Am Main - Munich - Ljubljana	726
572	Frankfurt Am Main - Leipzig - Dresden - Wroclaw - Lodz - Warsaw	1032
573	Brussels - Luxembourg - Paris - Lyon - Marseille	1252
574	Frankfurt Am Main - Munich - Ljubljana - Venice	944
575	Istanbul - Thessaloniki - Skopje - Pristina	823
576	Ljubljana - Venice - Bologna - Bari - Napoli	1201

577	Groningen - Bremen - Hannover - Leipzig - Munich	908
578	Bari - Bologna - Venice - Ljubljana	962
579	Linz - Zürich - Basel - Paris	1115
580	Birmingham - London - Lille - Brussels - Liège - Aachen - Cologne - Düsseldorf - Ruhrgebiet (Essen)	796
581	Budapest - Cluj-Napoca - Kosice	808
582	Gdansk - Warsaw - Krakow	655
583	Bratislava - Brno - Prague - Munich - Frankfurt Am Main	1009
584	Liverpool - Birmingham - London - Lille - Gent - Antwerpen - Rotterdam - Utrecht	831
585	Barcelona - Zaragoza - Bordeaux - Rouen	1307
586	Aarhus - Kiel - Hamburg - Bremen - Utrecht - Eindhoven - Liège - Brussels - Lille - London	1382
587	Cologne - Düsseldorf - Ruhrgebiet (Essen) - Hannover - Hamburg - Kiel	527
588	Moscow - St. Petersburg - Tallinn	977
589	Gent - Brussels - Luxembourg - Saarbrücken - Mannheim - Stuttgart - Munich	799
590	Karlsruhe - Strasbourg - Luxembourg - Liège - Eindhoven - Rotterdam	636
591	Riga - Tallinn - St. Petersburg - Helsinki - Tampere	1130
592	St. Petersburg - Helsinki - Tampere	508
593	Cologne - Frankfurt Am Main - Mannheim - Karlsruhe	307
594	Lyon - Marseille - Toulon	344
595	Brno - Ostrava - Krakow - Warsaw	575
596	Grenoble - Geneva - Paris - Luxembourg - Liège - Eindhoven - Rotterdam	1315
597	Berlin - Hamburg - Copenhagen - Gothenburg	845
598	Cologne - Frankfurt Am Main - Leipzig	533
599	Leeds - London - Lille - Gent - Antwerpen - Eindhoven - Utrecht	818
600	Linz - Munich - Leipzig - Ruhrgebiet (Essen)	1034
601	Ljubljana - Linz - Zürich	891
602	Frankfurt Am Main - Munich - Verona - Bologna - Florence - Rome	1240
603	Minsk - St. Petersburg - Tallinn	1055
604	Leeds - London - Lille - Brussels - Antwerpen - Rotterdam - Utrecht - Ruhrgebiet (Essen)	1000
605	Kiel - Hamburg - Berlin - Dresden - Prague - Stuttgart - Zürich	1291
606	Düsseldorf - Cologne - Aachen - Liège - Luxembourg - Strasbourg	499
607	Bologna - Venice - Vienna	689
608	Barcelona - Zaragoza - Bordeaux - Rouen - Lille	1538
609	Turin - Milano - Bologna - Venice - Vienna	1013
610	Basel - Strasbourg - Luxembourg - Brussels	533
611	Kosice - Bratislava - Budapest - Vienna	807
612	Kiel - Hamburg - Hannover - Frankfurt Am Main - Mannheim	618
613	Cologne - Aachen - Liège - Brussels - Lille	303
614	Brussels - Luxembourg - Saarbrücken	298
615	Düsseldorf - Cologne - Aachen - Liège - Luxembourg - Saarbrücken	391
616	Barcelona - Montpellier - Marseille - Grenoble - Turin - Milano - Bologna - Venice	1423
617	Krakow - Rzeszow - Lublin	306
618	Aachen - Liège - Luxembourg - Strasbourg - Basel - Zürich	604
619	Budapest - Ljubljana - Munich - Stuttgart - Mannheim - Saarbrücken	1238
620	Lodz - Katowice - Ostrava - Prague	611
621	Amsterdam - Utrecht - Hannover - Leipzig - Dresden	703
622	Brussels - Lille - Rouen - Bordeaux - Toulouse	1149
623	Basel - Karlsruhe - Stuttgart - Prague	688
624	Helsinki - St. Petersburg - Minsk	1065
625	Newcastle Upon Tyne - Leeds - London - Lille - Gent - Antwerpen - Rotterdam	897
626	Mannheim - Stuttgart - Zürich - Milano - Turin	708
627	Luxembourg - Saarbrücken - Mannheim - Stuttgart	373
628	Frankfurt Am Main - Munich - Linz	575
629	Dresden - Prague - Stuttgart - Mannheim	701
630	Budapest - Vienna - Venice - Bologna - Milano - Turin	1233
631	Lyon - Geneva - Basel - Karlsruhe - Mannheim	608
632	Glasgow - Manchester - Birmingham - London - Lille - Gent - Antwerpen - Eindhoven - Rotterdam	1164
633	Amsterdam - Utrecht - Groningen - Bremen - Hannover - Berlin - Poznan - Warsaw	1271
634	Marseille - Grenoble - Geneva - Zürich - Stuttgart	857
635	Aachen - Cologne - Frankfurt Am Main	237
636	Aarhus - Kiel - Hamburg - Hannover - Frankfurt Am Main	791
637	Amsterdam - Rotterdam - Antwerpen - Brussels - Lille - Rouen	540
638	Rotterdam - Eindhoven - Liège - Luxembourg - Saarbrücken	448
639	Antwerpen - Gent - Lille - London - Birmingham	547
640	Bremen - Groningen - Utrecht	332
641	Sarajevo - Zagreb - Vienna	704
642	Stuttgart - Munich - Verona	590
643	Liverpool - Birmingham - London - Lille - Brussels - Antwerpen - Eindhoven - Utrecht - Ruhrgebiet (Essen)	1051
644	Nice - Genoa - Milano - Zürich - Stuttgart	754
645	Frankfurt Am Main - Munich - Linz - Verona	1102
646	Belgrade - Zagreb - Ljubljana - Linz - Zürich	1377
647	Hannover - Munich - Linz - Vienna	984
648	Florence - Bologna - Verona - Munich - Frankfurt Am Main	986
649	Amsterdam - Rotterdam - Antwerpen - Brussels - Luxembourg - Paris - Nantes	1103
650	Ljubljana - Munich - Stuttgart	569
651	Krakow - Ostrava - Brno - Vienna	430
652	Birmingham - London - Lille - Gent - Antwerpen - Eindhoven	626
653	Milano - Geneva - Paris - Rouen	903
654	Genoa - Milano - Zürich	382
655	Brno - Ostrava - Katowice - Wroclaw - Poznan - Berlin - Hamburg - Copenhagen	1386
656	Katowice - Ostrava - Prague - Munich	770
657	Brussels - Lille - London - Leeds - Newcastle Upon Tyne	789
658	Prague - Linz - Verona - Brescia - Milano - Turin	1025
659	Birmingham - London - Lille - Paris - Lyon	1051
660	Bremen - Hannover - Frankfurt Am Main - Mannheim - Karlsruhe	572
661	Rome - Florence - Genoa - Milano - Geneva - Basel - Strasbourg	1234
662	Istanbul - Bucharest - Belgrade - Podgorica	1521
663	Brno - Vienna - Zagreb	460
664	Copenhagen - Kiel - Hamburg - Hannover	591
665	Basel - Geneva - Milano - Bologna - Venice	852
666	Munich - Prague - Dresden - Wroclaw	727
667	Gdansk - Poznan - Berlin - Hamburg	782
668	London - Lille - Rouen - Bordeaux - Toulouse - Montpellier	1523
669	Brussels - Luxembourg - Strasbourg	406
670	Hannover - Frankfurt Am Main - Mannheim - Karlsruhe	456
671	Gothenburg - Copenhagen - Hamburg - Hannover - Ruhrgebiet (Essen)	960
672	Bratislava - Brno - Prague	305
673	Lille - Paris - Lyon - Marseille - Nice	1088
674	Verona - Venice - Vienna	660
675	Bremen - Hannover - Leipzig - Frankfurt Am Main - Mannheim - Saarbrücken	907
676	Amsterdam - Rotterdam - Antwerpen - Gent - Lille - London - Leeds - Manchester - Edinburgh	1191
677	Budapest - Vienna - Venice	770
678	Linz - Verona - Bologna - Florence - Rome	1020
679	Hannover - Utrecht - Rotterdam	377
680	Aachen - Eindhoven - Rotterdam	196
681	Leipzig - Munich - Linz - Vienna	778
682	Rome - Florence - Genoa - Nice - Toulon	772
683	Amsterdam - Utrecht - Ruhrgebiet (Essen) - Leipzig - Dresden - Prague - Brno	1053
684	Leipzig - Frankfurt Am Main - Mannheim	432
685	Cologne - Aachen - Liège - Brussels - Lille - London - Leeds - Manchester	907
686	Berlin - Dresden - Prague - Linz - Verona	1059
687	Montpellier - Toulouse - Bordeaux - Rouen	1037
688	Budapest - Ljubljana - Munich - Frankfurt Am Main - Cologne	1317
689	Brussels - Gent - Lille - London - Leeds - Manchester - Glasgow	1033
690	Bologna - Bari - Napoli - Palermo	1495
691	Gent - Brussels - Luxembourg - Strasbourg - Basel - Zürich	662
692	Eindhoven - Liège - Brussels - Lille	295
693	Basel - Geneva - Grenoble - Marseille	638
694	Brussels - Luxembourg - Paris - Geneva	1037
695	Ostrava - Brno - Vienna	279
696	Bordeaux - Lyon - Grenoble - Turin - Genoa	966
697	Bilbao - Toulouse - Lyon	892
698	Helsinki - St. Petersburg - Minsk - Vilnius	1231
699	Frankfurt Am Main - Munich - Zürich - Geneva - Grenoble - Marseille	1310
700	Lodz - Warsaw - Vilnius	539
701	Napoli - Bari - Bologna - Milano - Zürich	1293
702	Amsterdam - Utrecht - Ruhrgebiet (Essen) - Leipzig	630
703	Kaliningrad - Vilnius - Warsaw	739
704	Dresden - Prague - Linz - Verona - Brescia - Milano	1030
705	Düsseldorf - Ruhrgebiet (Essen) - Hannover - Leipzig	504
706	Gent - Lille - London - Birmingham - Manchester	620
707	Groningen - Bremen - Hannover - Leipzig - Dresden - Prague	751
708	Antwerpen - Eindhoven - Utrecht - Hannover - Leipzig - Dresden - Prague	959
709	Mannheim - Stuttgart - Munich - Ljubljana - Zagreb	823
710	Brescia - Verona - Munich - Frankfurt Am Main	811
711	Bremen - Utrecht - Eindhoven - Antwerpen - Brussels	512

712	Brescia - Milano - Zürich - Stuttgart	533
713	Liège - Luxembourg - Strasbourg - Basel - Geneva - Milano	994
714	Gdansk - Warsaw - Lublin - Rzeszow	697
715	Poznan - Warsaw - Lublin - Rzeszow	594
716	Lille - Rouen - Rennes	514
717	Lille - London - Birmingham - Liverpool	572
718	Dresden - Wroclaw - Katowice - Warsaw	698
719	Luxembourg - Liège - Eindhoven - Utrecht	305
720	Mannheim - Stuttgart - Munich - Ljubljana - Venice	916
721	Madrid - Bilbao - Toulouse - Montpellier	985
722	Dresden - Leipzig - Ruhrgebiet (Essen) - Düsseldorf	555
723	Lyon - Grenoble - Turin - Milano - Bologna - Venice	773
724	Budapest - Belgrade - Podgorica	725
725	Geneva - Milano - Genoa	416
726	Porto - Bilbao - Toulouse	1020
727	Lyon - Grenoble - Turin - Milano - Brescia - Verona	586
728	Brussels - Luxembourg - Strasbourg - Karlsruhe	486
729	Brno - Prague - Stuttgart - Mannheim	755
730	Grenoble - Marseille - Toulon	340
731	Barcelona - Montpellier - Lyon - Geneva - Zürich - Munich	1270
732	Cologne - Frankfurt Am Main - Munich - Verona - Bologna - Milano - Turin	1374
733	Aarhus - Kiel - Hamburg - Bremen - Ruhrgebiet (Essen)	691
734	Groningen - Bremen - Hamburg	276
735	Geneva - Paris - Luxembourg - Brussels - Antwerpen - Rotterdam	1177
736	Lodz - Warsaw - Minsk	615
737	Ruhrgebiet (Essen) - Leipzig - Munich - Ljubljana - Zagreb	1310
738	Liège - Luxembourg - Saarbrücken - Mannheim	362
739	Genoa - Turin - Grenoble	367
740	Tirana - Podgorica - Sarajevo - Zagreb - Ljubljana - Venice	1061
741	Brussels - Luxembourg - Paris - Geneva - Grenoble - Turin	1378
742	Krakow - Ostrava - Prague - Stuttgart	930
743	Munich - Zürich - Basel - Paris - Rouen	1013
744	Aarhus - Kiel - Copenhagen - Stockholm	1203
745	Rouen - Paris - Basel - Zürich	721
746	Berlin - Poznan - Warsaw - Krakow	797
747	Kiel - Hamburg - Bremen - Utrecht - Rotterdam	558
748	Bordeaux - Rouen - Lille - Gent - Antwerpen - Eindhoven - Rotterdam	1123
749	Düsseldorf - Cologne - Aachen - Liège - Brussels - Lille - London - Leeds - Manchester	942
750	Grenoble - Geneva - Basel - Karlsruhe - Mannheim	600
751	Hannover - Ruhrgebiet (Essen) - Utrecht	405
752	Strasbourg - Luxembourg - Liège - Eindhoven - Utrecht	536
753	Düsseldorf - Cologne - Frankfurt Am Main - Mannheim - Karlsruhe	342
754	Gent - Brussels - Luxembourg - Saarbrücken - Mannheim - Stuttgart	599
755	Munich - Ljubljana - Zagreb - Sarajevo	862
756	Cologne - Frankfurt Am Main - Mannheim - Karlsruhe - Basel - Geneva - Grenoble	843
757	Basel - Geneva - Milano - Genoa - Florence	853
758	Budapest - Bucharest - Istanbul	1338
759	Birmingham - London - Lille	428
760	Budapest - Belgrade - Podgorica - Tirana	866
761	Manchester - Leeds - London - Lille - Rouen	835
762	Frankfurt Am Main - Leipzig - Dresden - Wroclaw - Katowice - Krakow	963
763	Bratislava - Budapest - Ljubljana	601
764	Gdansk - Warsaw - Katowice	655
765	Düsseldorf - Cologne - Aachen - Liège - Brussels - Lille	338
766	Antwerpen - Brussels - Luxembourg - Saarbrücken - Mannheim	469
767	Catania - Napoli - Bari - Bologna - Verona	1508
768	Geneva - Paris - Rouen	615
769	Milano - Bologna - Venice	334
770	Bologna - Milano - Zürich - Stuttgart - Mannheim	774
771	Basel - Zürich - Munich - Leipzig - Berlin - Hamburg - Copenhagen	1490
772	Geneva - Paris - Lille	692
773	Kosice - Ostrava - Prague	659
774	Frankfurt Am Main - Leipzig - Berlin - Poznan	776
775	Basel - Geneva - Milano - Bologna	713
776	Rotterdam - Utrecht - Hannover - Munich - Linz - Vienna	1361
777	Podgorica - Sarajevo - Zagreb	577
778	Paris - Lyon - Marseille - Nice - Genoa - Florence - Rome	1524
779	Linz - Verona - Brescia - Milano	674
780	Basel - Paris - Bordeaux	1049
781	Frankfurt Am Main - Mannheim - Saarbrücken - Paris - Lille - London - Leeds - Manchester	1362
782	Geneva - Zürich - Stuttgart	449
783	Toulon - Nice - Genoa - Milano - Zürich	693
784	Bologna - Milano - Turin - Grenoble - Lyon	634
785	Berlin - Dresden - Prague - Linz - Ljubljana	905
786	Lyon - Paris - Saarbrücken	787
787	Hamburg - Hannover - Frankfurt Am Main - Mannheim - Saarbrücken - Luxembourg	771
788	Mannheim - Stuttgart - Zürich - Milano - Genoa - Florence - Rome	1168
789	Hannover - Frankfurt Am Main - Mannheim - Saarbrücken	513
790	Aarhus - Kiel - Hamburg - Bremen - Groningen - Utrecht - Eindhoven - Antwerpen - Brussels	990
791	Brescia - Milano - Geneva - Paris - Lille - London	1318
792	Utrecht - Ruhrgebiet (Essen) - Hannover - Leipzig - Munich - Linz - Vienna	1421
793	Krakow - Warsaw - Poznan - Berlin - Hannover - Ruhrgebiet (Essen)	1291
794	Brescia - Verona - Munich - Leipzig - Ruhrgebiet (Essen)	1270
795	Birmingham - London - Lille - Gent - Antwerpen - Rotterdam - Utrecht - Groningen	857
796	Brno - Vienna - Ljubljana	466
797	Karlsruhe - Basel - Geneva - Grenoble - Turin	749
798	Saarbrücken - Luxembourg - Liège - Eindhoven - Rotterdam - Utrecht	498
799	Eindhoven - Antwerpen - Brussels - Luxembourg - Saarbrücken - Mannheim	548
800	Dresden - Prague - Stuttgart - Karlsruhe - Strasbourg - Saarbrücken	831
801	Geneva - Paris - Rennes	808
802	Hamburg - Berlin - Dresden - Prague - Linz	788
803	Pristina - Podgorica - Sarajevo - Zagreb - Vienna	1134
804	Eindhoven - Aachen - Liège - Brussels - Luxembourg - Paris - Lyon	1201
805	Frankfurt Am Main - Munich - Prague - Ostrava	1045
806	Eindhoven - Aachen - Cologne - Frankfurt Am Main - Munich - Prague	1037
807	Copenhagen - Hamburg - Bremen - Utrecht - Eindhoven - Antwerpen - Gent	931
808	Katowice - Ostrava - Brno - Vienna	361
809	Gdansk - Warsaw - Krakow - Ostrava	806
810	Ljubljana - Munich - Hannover - Ruhrgebiet (Essen)	1203
811	Hamburg - Berlin - Poznan - Warsaw	784
812	Brescia - Verona - Venice - Vienna - Budapest	944
813	Athens - Thessaloniki - Plovdiv	860
814	Lublin - Warsaw - Poznan	448
815	Gdansk - Warsaw - Lublin	551
816	Florence - Rome - Napoli	463
817	Antwerpen - Gent - Lille - London - Leeds	659
818	Berlin - Poznan - Warsaw - Vilnius - Riga	1218
819	Belgrade - Sofia - Skopje	576
820	Newcastle Upon Tyne - Leeds - London - Lille - Brussels - Antwerpen - Rotterdam - Utrecht	979
821	Prague - Linz - Verona	749
822	Montpellier - Toulouse - Bordeaux - Nantes - Rennes	854
823	Tallinn - Riga - Vilnius	555
824	Frankfurt Am Main - Hannover - Hamburg - Kiel - Copenhagen - Gothenburg	1199
825	Düsseldorf - Ruhrgebiet (Essen) - Bremen - Hamburg - Kiel	477
826	Toulon - Marseille - Montpellier - Toulouse	434
827	Lodz - Katowice - Ostrava - Prague - Munich	958
828	Stuttgart - Prague - Ostrava - Krakow - Warsaw	1199
829	Brussels - Liège - Eindhoven - Utrecht - Hannover	601
830	Linz - Munich - Stuttgart - Mannheim	547
831	Nantes - Bordeaux - Lyon - Marseille - Nice	1282
832	Genoa - Nice - Toulon - Marseille - Montpellier - Toulouse	745
833	Berlin - Dresden - Prague - Linz - Verona - Brescia - Milano - Turin	1335
834	Frankfurt Am Main - Cologne - Aachen - Liège - Brussels - Gent	425
835	Antwerpen - Gent - Lille - London - Birmingham - Liverpool	691
836	Lille - Rouen - Bordeaux - Toulouse - Montpellier	1268
837	Brno - Vienna - Linz - Zürich - Basel - Paris	1407
838	Leeds - London - Lille	540
839	Basel - Geneva - Grenoble - Turin	571
840	Poznan - Lodz - Katowice - Ostrava - Prague - Stuttgart	1236
841	Budapest - Vienna - Venice - Verona	880
842	Grenoble - Geneva - Basel - Strasbourg	485
843	Brno - Vienna - Venice - Bologna - Milano	1008
844	Bologna - Venice - Vienna - Budapest	909
845	Bratislava - Brno - Prague - Stuttgart - Mannheim	872
846	Lodz - Warsaw - Vilnius - Riga	808
847	Brussels - Liège - Aachen - Cologne - Frankfurt Am Main - Leipzig - Dresden	836
848	Glasgow - Manchester - Birmingham - London - Lille - Brussels - Antwerpen - Rotterdam - Utrecht	1157
849	Aarhus - Kiel - Hamburg - Berlin - Leipzig - Munich - Stuttgart	1353
850	Bologna - Milano - Geneva - Basel - Strasbourg	840
851	Gdansk - Warsaw - Krakow - Ostrava - Prague - Munich	1494
852	Bologna - Venice - Ljubljana - Zagreb - Belgrade - Podgorica - Tirana	1364

853	Skopje - Sofia - Belgrade - Zagreb - Vienna	1273
854	Cologne - Aachen - Liège - Brussels - Gent	253
855	Amsterdam - Rotterdam - Eindhoven - Liège - Luxembourg - Paris - Bordeaux - Toulouse	1517
856	Linz - Ljubljana - Zagreb	498
857	Ljubljana - Linz - Prague	595
858	Kiel - Hamburg - Hannover - Frankfurt Am Main - Mannheim - Karlsruhe - Strasbourg	762
859	Moscow - Minsk - Warsaw	1150
860	Catania - Napoli - Bari - Bologna - Venice	1516
861	Basel - Paris - Lille	720
862	Ruhrgebiet (Essen) - Hannover - Munich - Verona	1224
863	Ostrava - Katowice - Wroclaw - Dresden - Leipzig - Ruhrgebiet (Essen)	1036
864	Aarhus - Kiel - Hamburg - Berlin	591
865	Bordeaux - Bilbao - Madrid - Sevilla	1147
866	Gent - Lille - Paris - Geneva - Milano	1046
867	Lisbon - Porto - Bilbao - Toulouse	1305
868	Genoa - Milano - Zürich - Stuttgart	578
869	Copenhagen - Hamburg - Berlin - Poznan - Wroclaw - Katowice - Ostrava	1231
870	Florence - Bologna - Venice - Vienna	797
871	Copenhagen - Hamburg - Berlin - Poznan - Lodz	990
872	Karlsruhe - Basel - Geneva - Lyon	544
873	Karlsruhe - Stuttgart - Munich - Ljubljana - Venice	859
874	Brescia - Milano - Zürich	337
875	Bilbao - Bordeaux - Nantes - Rouen	970
876	Belgrade - Budapest - Bratislava	527
877	Florence - Genoa - Milano - Zürich - Stuttgart - Mannheim	914
878	Dresden - Prague - Stuttgart - Karlsruhe	644
879	Bratislava - Budapest - Bucharest	942
880	Ljubljana - Munich - Stuttgart - Mannheim	698
881	Leipzig - Frankfurt Am Main - Mannheim - Saarbrücken	553
882	Geneva - Grenoble - Marseille - Toulon	468
883	Belgrade - Budapest - Bratislava - Brno	644
884	Budapest - Belgrade - Podgorica - Pristina	946
885	Strasbourg - Basel - Zürich - Linz - Ljubljana - Zagreb	1221
886	Edinburgh - Newcastle Upon Tyne - Leeds - London - Lille - Gent - Antwerpen - Eindhoven - Rotterdam	1162
887	Ostrava - Prague - Stuttgart	779
888	Copenhagen - Hamburg - Berlin - Poznan - Warsaw - Krakow	1355
889	Leipzig - Munich - Zürich - Milano	938
890	Grenoble - Turin - Milano - Bologna - Venice	676
891	Mannheim - Stuttgart - Munich - Linz - Verona	1074
892	Geneva - Basel - Strasbourg	357
893	Gent - Brussels - Antwerpen - Eindhoven - Utrecht - Groningen - Bremen - Hamburg	706
894	Ljubljana - Linz - Zürich - Basel - Paris	1488
895	Budapest - Cluj-Napoca - Sofia - Skopje	1227
896	Frankfurt Am Main - Munich - Verona - Brescia - Milano - Genoa - Nice	1198
897	Prague - Linz - Ljubljana - Venice	813
898	Groningen - Utrecht - Rotterdam - Antwerpen - Brussels - Lille - London - Birmingham - Manchester	1015
899	Dresden - Leipzig - Hannover - Utrecht - Rotterdam	716
900	Cologne - Frankfurt Am Main - Leipzig - Dresden - Wroclaw - Lodz - Warsaw	1204
901	Antwerpen - Liège - Luxembourg - Strasbourg - Basel	584
902	Helsinki - St. Petersburg - Minsk - Warsaw	1562
903	Berlin - Dresden - Prague - Linz - Verona - Bologna	1190
904	Brescia - Verona - Linz - Prague	813
905	Brescia - Verona - Venice - Vienna	724
906	Brno - Prague - Stuttgart - Karlsruhe - Strasbourg	778
907	Copenhagen - Kiel - Hamburg - Berlin - Poznan	957
908	Aarhus - Kiel - Hamburg - Bremen - Utrecht - Eindhoven	832
909	Karlsruhe - Mannheim - Frankfurt Am Main - Leipzig	496
910	Kiel - Hamburg - Bremen - Utrecht	508
911	Kyiv - Kosice - Ostrava	1109
912	Berlin - Poznan - Warsaw - Lublin	693
913	Liège - Luxembourg - Saarbrücken	241
914	Catania - Napoli - Rome - Florence - Genoa	1203
915	Antwerpen - Gent - Lille - Rouen - Nantes - Bordeaux	1016
916	Eindhoven - Liège - Brussels - Lille - London - Leeds	835
917	Glasgow - Liverpool - Birmingham - London - Lille	889
918	Toulouse - Lyon - Geneva - Zürich	877
919	Basel - Strasbourg - Luxembourg - Brussels - Antwerpen - Eindhoven	662
920	Berlin - Leipzig - Munich - Verona - Brescia	1016
921	Katowice - Krakow - Rzeszow - Kyiv	879
922	Brno - Prague - Munich - Frankfurt Am Main - Cologne	1064
923	Copenhagen - Hamburg - Bremen - Groningen - Utrecht - Rotterdam - Antwerpen - Liège	996
924	Dresden - Prague - Stuttgart - Karlsruhe - Strasbourg	724
925	Bordeaux - Paris - Luxembourg - Liège - Eindhoven - Utrecht	1206
926	Barcelona - Zaragoza - Bordeaux - Nantes - Rennes	1124
927	Birmingham - London - Lille - Paris - Saarbrücken - Mannheim - Frankfurt Am Main	1186
928	Pristina - Podgorica - Sarajevo - Zagreb	798
929	Bologna - Milano - Geneva - Basel - Strasbourg - Luxembourg - Brussels	1246
930	Ljubljana - Zagreb - Sarajevo	493
931	Brussels - Liège - Aachen - Cologne - Frankfurt Am Main - Leipzig	735
932	Eindhoven - Antwerpen - Gent - Lille - London - Birmingham - Liverpool	770
933	Liège - Aachen - Cologne - Frankfurt Am Main - Munich - Prague	991
934	Gothenburg - Copenhagen - Hamburg - Bremen - Utrecht - Rotterdam	1056
935	Brno - Prague - Stuttgart - Karlsruhe	698
936	Düsseldorf - Cologne - Aachen - Liège - Brussels - Gent	288
937	Katowice - Wroclaw - Dresden - Leipzig - Hannover - Ruhrgebiet (Essen)	1004
938	Birmingham - London - Lille - Rouen	659
939	Leipzig - Frankfurt Am Main - Mannheim - Karlsruhe - Strasbourg	576
940	Karlsruhe - Stuttgart - Munich - Ljubljana - Zagreb	766
941	Frankfurt Am Main - Leipzig - Dresden - Wroclaw - Katowice	891
942	Antwerpen - Liège - Luxembourg - Paris - Lyon - Grenoble	1116
943	Gdansk - Poznan - Berlin - Hannover - Ruhrgebiet (Essen)	1020
944	Bilbao - Bordeaux - Rouen - Lille	1129
945	Berlin - Dresden - Wroclaw - Katowice	605
946	Brno - Bratislava - Budapest - Bucharest	1059
947	Brescia - Milano - Geneva - Basel - Strasbourg - Luxembourg - Brussels	1134
948	Aachen - Eindhoven - Utrecht - Groningen - Bremen	508
949	Bordeaux - Paris - Strasbourg	974
950	Bilbao - Bordeaux - Nantes - Rouen - Lille - London	1456
951	Bologna - Verona - Linz - Prague	880
952	Antwerpen - Brussels - Lille - London - Leeds - Newcastle Upon Tyne	839
953	Bologna - Milano - Geneva - Basel - Karlsruhe	891
954	Liège - Luxembourg - Paris - Lyon	911
955	Poznan - Berlin - Hannover - Ruhrgebiet (Essen)	739
956	Linz - Zürich - Basel - Strasbourg	723
957	Skopje - Sofia - Belgrade - Zagreb	937
958	Antwerpen - Rotterdam - Utrecht - Hannover - Munich - Linz - Vienna	1451
959	Amsterdam - Utrecht - Bremen - Hannover - Munich - Verona - Brescia	1508
960	Birmingham - London - Lille - Gent	494
961	Aachen - Eindhoven - Rotterdam - Utrecht - Groningen - Bremen - Hamburg - Copenhagen	994
962	Kyiv - Minsk - Warsaw - Poznan	1301
963	Lublin - Warsaw - Vilnius	586
964	Eindhoven - Antwerpen - Brussels - Luxembourg	304
965	Karlsruhe - Basel - Geneva - Grenoble - Turin - Genoa - Florence - Rome	1364
966	Saarbrücken - Mannheim - Stuttgart - Munich - Ljubljana - Zagreb	944
967	Cologne - Frankfurt Am Main - Munich - Linz	747
968	Groningen - Bremen - Ruhrgebiet (Essen)	404
969	Basel - Zürich - Linz - Vienna - Zagreb	1100
970	Gent - Brussels - Luxembourg - Saarbrücken - Mannheim - Stuttgart - Prague	1037
971	Berlin - Dresden - Wroclaw - Katowice - Ostrava	687
972	Basel - Karlsruhe - Mannheim - Frankfurt Am Main - Hannover - Hamburg - Kiel	860
973	Amsterdam - Utrecht - Hannover - Berlin - Poznan - Lodz	1054
974	Frankfurt Am Main - Mannheim - Karlsruhe - Strasbourg - Paris - Rouen	783
975	Genoa - Nice - Marseille - Montpellier - Toulouse - Bordeaux - Nantes	1269
976	Bratislava - Brno - Prague - Stuttgart - Karlsruhe - Strasbourg	895
977	Belgrade - Podgorica - Pristina	601
978	Bratislava - Budapest - Ljubljana - Venice - Verona - Brescia - Milano	1076
979	Nantes - Bordeaux - Lyon - Marseille - Toulon	1161
980	Frankfurt Am Main - Leipzig - Dresden - Wroclaw	708
981	Paris - Bordeaux - Bilbao - Madrid - Valencia	1517
982	Antwerpen - Liège - Luxembourg - Strasbourg	457
983	Rotterdam - Antwerpen - Gent - Lille - Rouen	440
984	Amsterdam - Utrecht - Bremen - Hannover - Berlin - Poznan	959
985	Gothenburg - Copenhagen - Hamburg - Bremen - Groningen - Utrecht	1035
986	Birmingham - London - Lille - Brussels - Liège - Aachen - Cologne	731

987	Eindhoven - Liège - Luxembourg - Paris - Lyon - Grenoble	1115
988	Mannheim - Karlsruhe - Basel - Geneva - Grenoble - Marseille	880
989	Aachen - Cologne - Frankfurt Am Main - Munich - Linz - Vienna	980
990	Antwerpen - Brussels - Luxembourg - Saarbrücken	348
991	Antwerpen - Eindhoven - Utrecht - Ruhrgebiet (Essen) - Hannover - Hamburg - Kiel - Aarhus	1034
992	Basel - Strasbourg - Luxembourg - Brussels - Liège	620
993	Aachen - Liège - Luxembourg - Saarbrücken - Mannheim	412
994	Bremen - Utrecht - Rotterdam - Eindhoven	453
995	Brno - Bratislava - Kosice - Kyiv	1313
996	Leipzig - Ruhrgebiet (Essen) - Utrecht - Rotterdam	643
997	Groningen - Bremen - Hannover - Munich - Zürich	1168
998	Munich - Verona - Bologna - Florence - Genoa - Nice - Toulon	1147
999	Grenoble - Turin - Milano - Brescia - Verona	489
1000	Amsterdam - Rotterdam - Antwerpen - Gent - Lille - Rouen - Rennes	791
1001	Grenoble - Geneva - Basel - Karlsruhe	536
1002	Aachen - Cologne - Frankfurt Am Main - Munich - Prague	941
1003	Düsseldorf - Ruhrgebiet (Essen) - Leipzig - Dresden - Wroclaw - Lodz - Warsaw	1125
1004	Kiel - Hamburg - Berlin - Dresden - Wroclaw - Katowice - Ostrava - Brno - Vienna	1313
1005	Montpellier - Lyon - Geneva - Zürich - Stuttgart - Munich	1061
1006	Montpellier - Marseille - Nice - Genoa - Florence - Rome	972
1007	Antwerpen - Brussels - Lille - London - Leeds - Manchester - Glasgow	1067
1008	Frankfurt Am Main - Leipzig - Dresden - Wroclaw - Lodz	914
1009	Lodz - Poznan - Berlin - Hannover - Ruhrgebiet (Essen)	926
1010	Geneva - Zürich - Linz - Vienna	939
1011	Liège - Brussels - Lille - London - Leeds - Manchester	792
1012	Aarhus - Kiel - Hamburg - Bremen - Ruhrgebiet (Essen) - Düsseldorf - Cologne	756
1013	Basel - Zürich - Linz - Vienna - Brno	888
1014	Antwerpen - Liège - Luxembourg	226
1015	Gothenburg - Copenhagen - Hamburg - Hannover - Munich	1322
1016	Bari - Bologna - Milano - Zürich	1054
1017	Copenhagen - Hamburg - Berlin - Poznan - Lodz - Katowice	1178
1018	Birmingham - London - Lille - Paris - Strasbourg - Karlsruhe - Stuttgart	1225
1019	Kyiv - Budapest - Vienna	1217
1020	Bucharest - Budapest - Ljubljana	1179
1021	Bremen - Utrecht - Eindhoven - Liège	490
1022	Antwerpen - Eindhoven - Utrecht - Groningen - Bremen	491
1023	Katowice - Ostrava - Prague - Stuttgart	861
1024	Ruhrgebiet (Essen) - Leipzig - Munich - Ljubljana - Venice	1403
1025	Geneva - Basel - Karlsruhe - Mannheim	472
1026	Katowice - Warsaw - Lublin	434
1027	Florence - Genoa - Milano - Zürich - Stuttgart - Karlsruhe	857
1028	Brussels - Luxembourg - Paris - Lyon - Marseille - Nice	1433
1029	Basel - Zürich - Linz	596
1030	Basel - Geneva - Milano - Brescia - Verona	665
1031	Hamburg - Berlin - Dresden - Prague - Linz - Verona - Brescia - Milano	1462
1032	Linz - Munich - Stuttgart - Mannheim - Saarbrücken	668
1033	Eindhoven - Liège - Brussels - Luxembourg - Strasbourg	600
1034	Brussels - Lille - London - Leeds - Newcastle Upon Tyne - Edinburgh	965
1035	Cologne - Frankfurt Am Main - Munich - Ljubljana - Zagreb	1023
1036	Antwerpen - Liège - Luxembourg - Strasbourg - Karlsruhe	537
1037	Cluj-Napoca - Budapest - Vienna	645
1038	Groningen - Bremen - Hannover - Munich - Stuttgart	1076
1039	Grenoble - Lyon - Paris - Saarbrücken	884
1040	Florence - Bologna - Verona - Munich - Leipzig - Ruhrgebiet (Essen)	1445
1041	Brno - Prague - Dresden - Leipzig - Hannover - Bremen - Ruhrgebiet (Essen) - Düsseldorf	1049
1042	Brussels - Gent - Lille - Paris - Geneva - Milano - Bologna - Venice	1431
1043	Bordeaux - Nantes - Rouen - Lille - Gent	963
1044	Bologna - Verona - Linz - Munich - Frankfurt Am Main - Cologne	1405
1045	Bilbao - Toulouse - Lyon - Grenoble	989
1046	Cologne - Düsseldorf - Ruhrgebiet (Essen) - Bremen - Hamburg - Copenhagen - Gothenburg	1010
1047	Grenoble - Turin - Milano - Bologna - Venice - Vienna	1226
1048	Cologne - Aachen - Liège - Brussels - Lille - London - Leeds	843
1049	Frankfurt Am Main - Munich - Zürich - Milano - Genoa	1031
1050	Liège - Aachen - Cologne - Frankfurt Am Main - Munich - Ljubljana - Vienna	1355
1051	Liège - Luxembourg - Saarbrücken - Strasbourg	348
1052	Brussels - Antwerpen - Eindhoven - Rotterdam - Utrecht - Hannover - Hamburg - Kiel	832
1053	Amsterdam - Utrecht - Bremen - Hannover - Leipzig - Munich - Linz	1304
1054	Luxembourg - Paris - Lyon	793
1055	Stuttgart - Zürich - Geneva - Lyon - Toulouse	1073
1056	Belgrade - Sofia - Thessaloniki	623
1057	Lille - Paris - Basel - Zürich - Linz - Vienna	1484
1058	Bologna - Milano - Turin - Grenoble	537
1059	Brno - Prague - Stuttgart - Mannheim - Saarbrücken	876
1060	Aarhus - Kiel - Hamburg - Hannover - Frankfurt Am Main - Mannheim	862
1061	Karlsruhe - Basel - Geneva - Grenoble - Marseille	816
1062	Turin - Grenoble - Marseille - Montpellier - Barcelona - Valencia	1279
1063	Rotterdam - Antwerpen - Gent - Lille - Rouen - Nantes - Bordeaux - Toulouse	1329
1064	Birmingham - London - Lille - Paris - Geneva	1120
1065	Napoli - Rome - Florence - Genoa - Nice	846
1066	Milano - Genoa - Nice - Marseille - Montpellier - Barcelona - Valencia	1271
1067	Leipzig - Dresden - Wroclaw - Lodz - Warsaw	671
1068	Cologne - Aachen - Liège - Brussels - Lille - London - Birmingham - Liverpool	875
1069	Antwerpen - Brussels - Luxembourg - Paris - Bordeaux - Toulouse	1349
1070	Bratislava - Brno - Prague - Stuttgart - Karlsruhe	815
1071	Thessaloniki - Sofia - Belgrade - Zagreb	984
1072	Copenhagen - Hamburg - Hannover - Frankfurt Am Main - Mannheim - Saarbrücken - Luxembourg	1073
1073	Basel - Strasbourg - Luxembourg	358
1074	Antwerpen - Liège - Luxembourg - Saarbrücken - Paris - Lyon - Marseille	1420
1075	Strasbourg - Basel - Geneva - Milano - Brescia - Verona	792
1076	Lublin - Warsaw - Vilnius - Riga	855
1077	Nantes - Rouen - Lille - Gent - Antwerpen - Eindhoven - Utrecht	860
1078	Brescia - Milano - Zürich - Stuttgart - Mannheim	662
1079	Tirana - Podgorica - Sarajevo - Zagreb	718
1080	Poznan - Gdansk - Warsaw - Vilnius - Riga	1357
1081	Budapest - Bucharest - Plovdiv	1122
1082	Birmingham - Leeds - London - Lille - Brussels - Liège - Aachen - Cologne - Düsseldorf	1052
1083	Lille - Paris - Geneva - Milano - Brescia - Verona	1127
1084	Dresden - Leipzig - Hannover - Utrecht	666
1085	Utrecht - Ruhrgebiet (Essen) - Hannover - Berlin - Poznan - Warsaw	1191
1086	Düsseldorf - Ruhrgebiet (Essen) - Leipzig - Munich - Linz	1064
1087	Luxembourg - Saarbrücken - Mannheim - Stuttgart - Munich - Ljubljana - Vienna	1284
1088	Rouen - Lille - Gent - Antwerpen - Eindhoven - Utrecht	509
1089	Berlin - Hamburg - Kiel	347
1090	Bordeaux - Nantes - Paris - Basel - Karlsruhe - Mannheim - Frankfurt Am Main	1496
1091	Rouen - Paris - Basel - Zürich - Stuttgart	917
1092	Manchester - Leeds - London - Lille - Paris - Saarbrücken	1170
1093	Eindhoven - Liège - Luxembourg - Saarbrücken	348
1094	Karlsruhe - Stuttgart - Munich - Verona	662
1095	Karlsruhe - Basel - Geneva - Grenoble - Marseille - Toulon - Nice	1011
1096	Mannheim - Stuttgart - Prague - Ostrava - Krakow - Warsaw	1328
1097	Aachen - Liège - Brussels - Luxembourg - Paris - Lyon	1105
1098	Karlsruhe - Strasbourg - Luxembourg	311
1099	Eindhoven - Antwerpen - Brussels - Luxembourg - Strasbourg - Karlsruhe	615
1100	Frankfurt Am Main - Hannover - Bremen - Groningen	599
1101	Brescia - Milano - Geneva - Paris - Lille	1063
1102	Kiel - Copenhagen - Stockholm	959
1103	Eindhoven - Liège - Brussels - Lille - London - Leeds - Newcastle Upon Tyne	983
1104	Frankfurt Am Main - Mannheim - Karlsruhe - Strasbourg - Paris - Lille - London - Leeds	1400
1105	Budapest - Bucharest - Chisinau	1156
1106	Luxembourg - Saarbrücken - Mannheim - Stuttgart - Prague	811
1107	Brno - Bratislava - Kosice	522
1108	Brescia - Verona - Munich - Frankfurt Am Main - Cologne	983
1109	Eindhoven - Rotterdam - Utrecht - Hannover	477
1110	Düsseldorf - Cologne - Aachen - Liège - Brussels - Lille - London - Leeds	878
1111	Thessaloniki - Sofia - Belgrade - Zagreb - Vienna	1320
1112	Bordeaux - Lyon - Geneva - Zürich - Stuttgart	1087
1113	Basel - Karlsruhe - Mannheim - Frankfurt Am Main - Leipzig	674
1114	Basel - Zürich - Linz - Prague - Dresden	952

1115	Antwerpen - Liège - Luxembourg - Strasbourg - Basel - Geneva	814
1116	Bari - Bologna - Venice - Ljubljana - Munich	1331
1117	Edinburgh - Manchester - Birmingham - London - Lille - Gent - Antwerpen - Rotterdam - Utrecht	1123
1118	Madrid - Zaragoza - Bordeaux - Nantes - Rennes	1130
1119	Gothenburg - Copenhagen - Hamburg - Bremen - Groningen	865
1120	Gent - Lille - London - Leeds	606
1121	Cologne - Frankfurt Am Main - Munich - Ljubljana	898
1122	Gent - Brussels - Luxembourg - Saarbrücken - Mannheim	470
1123	Mannheim - Stuttgart - Zürich - Milano - Genoa - Nice	883
1124	Basel - Zürich - Linz - Ljubljana	969
1125	Budapest - Ljubljana - Venice - Bologna - Florence	884
1126	Stuttgart - Munich - Prague - Ostrava - Katowice - Wroclaw	1153
1127	Brno - Vienna - Venice	674
1128	Aachen - Liège - Luxembourg - Strasbourg - Basel	526
1129	Gent - Lille - London - Birmingham - Liverpool	638
1130	Ruhrgebiet (Essen) - Leipzig - Dresden - Wroclaw	771
1131	Aarhus - Kiel - Hamburg - Bremen - Groningen	611
1132	Antwerpen - Eindhoven - Utrecht - Bremen - Hannover	578
1133	Mannheim - Stuttgart - Prague - Ostrava	908
1134	Düsseldorf - Cologne - Aachen - Liège - Brussels - Lille - London - Birmingham - Liverpool	910
1135	Helsinki - St. Petersburg - Minsk - Vilnius - Kaliningrad	1549
1136	Lublin - Warsaw - Lodz - Wroclaw	489
1137	Gothenburg - Copenhagen - Hamburg - Hannover - Munich - Stuttgart	1522
1138	Munich - Prague - Ostrava - Krakow - Rzeszow	999
1139	Hamburg - Hannover - Frankfurt Am Main - Mannheim - Karlsruhe - Strasbourg - Paris - Rouen	1239
1140	Lille - London - Leeds - Newcastle Upon Tyne	688
1141	Grenoble - Lyon - Paris - Luxembourg - Liège	1008
1142	Hannover - Berlin - Poznan - Lodz - Katowice - Ostrava	960
1143	Karlsruhe - Stuttgart - Munich - Ljubljana	641
1144	Marseille - Nice - Genoa - Florence - Rome - Napoli	1027
1145	Brescia - Verona - Venice - Ljubljana - Zagreb - Sarajevo - Podgorica - Tirana	1235
1146	Brno - Prague - Stuttgart - Mannheim - Saarbrücken - Luxembourg - Brussels	1174
1147	Kiel - Hamburg - Hannover - Frankfurt Am Main - Mannheim - Saarbrücken	739
1148	Krakow - Ostrava - Prague - Stuttgart - Mannheim	1059
1149	Groningen - Bremen - Hannover - Berlin - Poznan - Warsaw	1064
1150	Cologne - Frankfurt Am Main - Munich - Linz - Verona	1274
1151	Linz - Verona - Brescia - Milano - Turin	803
1152	Ljubljana - Zagreb - Belgrade - Podgorica	866
1153	Manchester - Leeds - London - Lille - Paris - Strasbourg	1249
1154	Linz - Prague - Ostrava - Katowice - Lodz - Poznan	1020
1155	Madrid - Valencia - Barcelona - Montpellier - Marseille - Toulon - Nice	1303
1156	Podgorica - Sarajevo - Zagreb - Vienna	913
1157	Berlin - Hannover - Ruhrgebiet (Essen) - Utrecht - Eindhoven - Antwerpen - Gent - Lille - London - Birmingham	1369
1158	Bucharest - Iasi - Kyiv - Lublin	1459
1159	Belgrade - Zagreb - Ljubljana - Linz	859
1160	Gent - Lille - Rouen - Bordeaux - Toulouse	1114
1161	Poznan - Lodz - Katowice - Ostrava - Prague - Munich - Zürich	1437
1162	Rotterdam - Amsterdam - Utrecht - Ruhrgebiet (Essen) - Leipzig - Dresden - Wroclaw - Lodz - Warsaw	1369
1163	Nantes - Paris - Basel - Karlsruhe - Stuttgart	1118
1164	Leipzig - Hannover - Utrecht	565
1165	Lodz - Katowice - Krakow - Ostrava - Prague - Munich - Stuttgart	1299
1166	Amsterdam - Utrecht - Ruhrgebiet (Essen) - Hannover - Leipzig - Munich - Verona	1462
1167	Groningen - Utrecht - Rotterdam	220
1168	Chisinau - Iasi - Bucharest	485
1169	Cluj-Napoca - Bucharest - Istanbul	988
1170	Leipzig - Berlin - Hamburg	426

D AI Statement

For this thesis, Artificial Intelligence (AI) has been made use of as a supportive tool. Due to personal scepticism around the rise of AI and how it might impact people's ability to do research work and critical thinking by themselves, it was used as little as possible. The goal was to use AI only if after having tried something thoroughly without it, no good solution could be found. In the end it was used mostly for coding, specifically to write functions, draw the maps, and increase computational efficiency. The first two were done by writing clear prompts asking for specific outputs based on inputs, and the last point was done by feeding code snippets and asking for how computation could be accelerated while keeping the outputs. A small amount of AI was also used to find specific literature, and for spellchecking and proofreading at the end of the process, a well as to help with the final research paper. The most important rule used was to always check the code outputs to understand as much as possible, for the literature, to check any suggestion and any quote directly in the paper, and for any suggestions to changes in the text, to always re-read and use own wording. If the paper couldn't be retrieved, then it was simply not taken into consideration. The AI agents used were at first ChatGPT, before swapping to Anthropic's Claude in the later half of the thesis process, based on recommendations by fellow students.

E Research paper

Long-distance European rail network under operator competition

Samuel Bichsel

Abstract

The European long-distance passenger rail market is being opened to competition to make rail more competitive against air and road. This paper investigates what a European long-distance rail network could look like when operators compete on lines and frequencies. A customised Transit Network Design and Frequency Setting Problem (TNDFSP) methodology is developed in which operators iteratively solve a mixed-integer linear program to select lines and set frequencies, taking the previous plans of their competitors and an estimate of expected demand as given, while passengers are assigned to the resulting network with a capacity-constrained logit model with elastic demand. Applied to a network of 123 European cities with 11 national and 3 private operators, the model converges after 15 iterations. Competing operators concentrate service in the high-demand west, serve 76% of the total demand (65% of it without transfers) and leave peripheral areas with minimal service. A single profit-maximising operator produces a similar network that serves less demand (72%), whereas a demand-maximising operator serves 98%. Removing the transfer barrier between operators raises the absolute demand served by about 2% at roughly 10% lower operator profits. Within the limitations of the model, these results suggest that the objective of the operator matters more for passengers than the market structure, and that subsidies or service obligations may be needed to maintain service in low-demand regions.

Keywords: passenger rail competition, network design, long-distance rail

1. Introduction

With the goal of reducing CO2 emissions in the context of climate change, rail is viewed as an attractive and sustainable option for long-distance travel (Cats, 2025). The European Union has therefore introduced directives aimed at improving cross-border ticketing and booking, removing barriers to entry for new operators and increasing cooperation between infrastructure managers to allow for more cross-border capacity (European Commission, 2025). These measures are intended to open the market to new, private competitors that challenge the national incumbents on passenger lines, leading to increased competition on service levels.

A decade after the 2016 railway package, the long-distance passenger rail sector has become progressively more competitive, with new operators coexisting with the incumbent state operators (Battilocchi et al., 2026). This trend is set to continue, notably with competition arriving in the Channel Tunnel from the early 2030s from both private and public operators (Railway Gazette International, 2026; Stone, 2026). Lower barriers to entry and fair, non-discriminatory access make it relevant to investigate how competition between service providers can shape European passenger rail services.

The goal of this paper is to investigate what a European long-distance rail line network could look like under open competition on service levels, considering the implications for both operators and passengers. To do so, a modified Transit Network Design and Frequency Setting Problem (TNDFSP) is developed that includes multiple, strategically interacting operators, and applied to a network of 123 European cities and tested for its network, passenger and operator performance.

The remainder of this paper is structured as follows. Section 2 reviews the literature on competition in European rail, modelling approaches to long-distance competition and the TNDFSP. Section 3 presents the methodology and Section 4 the case study. Section 5 presents the results, and Section 6 discusses them, including the limitations of the research, and concludes.

2. Literature review

2.1. Experiences of European passenger rail competition

In ex-post, national case studies for long-distance lines in the EU, on-track rail operator competition is generally found to be beneficial for customers. Frequencies on lines with competition are found to be higher in all cases examined for Austria (Tomeš et al., 2016), Italy (Antoniazzi et al., 2020; Bergantino et al., 2015; Desmaris & Croccolo, 2018), Slovakia (Kvizda & Solnička, 2019), Sweden (Vigren, 2017), and the Czech Republic (Tomeš et al., 2016) in some cases by up to 50% more daily trips. This is due to incumbents only rarely reducing their frequencies despite the new services provided by the entrants, in order to retain their position in the market. Next to the benefits for customers through higher capacity and more options, the higher frequencies also lead to a more efficient usage of the existing rail infrastructure (Antoniazzi et al., 2020). However, in some cases, such as on the Prague – Ostrava route in the Czech Republic, this has led to infrastructure reaching maximum capacity, consequently delaying regional traffic and making it difficult to slot in freight trains (Tomeš et al., 2014). Further, public service operators keeping or increasing their service on routes with competition, losing profits to their competitor, can lead to cuts in service on other, less profitable parts of the network or times in the day due to less cross-subsidies being available (Steer Davies Gleave, 2016). Examples of this exist in Italy and the Czech Republic, where the entry of competitors forced incumbents to either eliminate services or redistribute service from off-peak to peak-hour (Bergantino et al., 2015; Tomeš et al., 2016)

The higher frequencies, combined with usually lower ticket prices, have led to significantly higher ridership across all markets (Antoniazzi et al., 2020; Cascetta & Coppola, 2014; de Rose et al., 2024; Tomeš & Jandová, 2018). Some of this ridership comes from other Intercity rail services (Desmaris & Croccolo, 2018) but also from other modes such as intercity buses, air and carpooling (Behrens & Pels, 2012; Desmaris & Croccolo, 2018; Laroche & Lamatkhanova, 2022), increasing the modal share of rail. However, despite this increase in ridership, the cheaper pricing and splitting of the demand has led to issues of financial profitability for the rail operators. On-track competition thus sees benefits to users in terms of fares and services, but also a loss of profitability in the industry, which can lead to a net decrease in social welfare (Álvarez-SanJaime et al., 2016).

2.2. Modelling of public transport operator competition

Rail competition models and simulations, similarly to the ex-post case studies presented in the previous section, commonly look at the duopoly approach of a new, private entrant challenging the incumbent national provider, as well as intermodal competition with airlines.

Álvarez-SanJaime et al. (2015) simulate competition for a duopoly and triopoly between an incumbent, an entrant rail operator as well as an airline in the Spanish market, with both welfare- and profit-maximising functions. The model is a two-stage game, solved by finding the Nash equilibrium for the subgames, where transport operators first independently set frequencies, and then, knowing the frequencies of their competitors, set prices accordingly. They find that a welfare maximising operator disciplines the market competition in favour of passengers, as otherwise full privatisation

increases prices and reduces total services. Ivaldi & Vibes (2007) utilise a supply and demand model where consumers choose a transport mode and an operator based on a discrete choice model to travel on the Köln – Berlin line, and operators strategically decide on prices for the services they provide. They simulate different scenarios, such as the entry of a standard rail operator, a low-cost airline, a low-cost rail operator, and the implementation of a kerosene tax. Findings include the reduction of prices of the incumbent air and rail providers in all scenarios. Cherbonnier et al. (2018) model an oligopoly situation for both intermodal and intramodal competition to investigate short-term pricing competition, where passengers select mode and operator based on quality and prices, and operators only set prices. Findings include that opening to competition does not guarantee a decrease in prices in favour of passengers. Finally, Broman & Eliasson (2019) use a stylised two-stage simulation model where the interaction happens between rail operators and the infrastructure manager. Operators announce their desired frequencies, the infrastructure manager then sets the departure times, and finally the operators set their prices accordingly. The passengers in this model are distributed uniformly across the day. Their findings show that duopoly yields a significant increase in welfare compared to a monopoly, but that operators are incentivised to monopolise.

2.3. The TNDFSP approach

Transit Network Design and Frequency Setting Problem (TNDFSP), also termed transit network design problem (TNDP) or transit route network design problem (TRNDP), is a type of methodology used to plan and design transit networks by creating a set of lines and timetables (Guihaire & Hao, 2008). Extensive literature reviews discussing the TNDFSP methodology more in-depth include Durán-Micco & Vansteenwegen (2022a), Guihaire & Hao (2008), Kepaptsoglou & Karlaftis (2009) and Owais (2026).

These approaches most commonly take as an input a network of edges and nodes as well as a demand matrix and output a design of a network of lines and their corresponding frequencies. The goal is to optimise an objective for a transit operator, passengers, or a mix of the two (Owais, 2026). These objectives are optimised for by translating possible line configurations into scores that can be compared between each other (Grolle, 2020) while restricted by various kinds of constraints such as maximum number of lines, minimum load factors, and upper limits on budget and fleet size (Kepaptsoglou & Karlaftis, 2009).

Most commonly, TNDFSP problems are made up of three parts: route generation, line configuration and passenger assignment (Kepaptsoglou & Karlaftis, 2009). During the route generation procedure, a shortest-path algorithm, usually combined with a set of restrictions such as maximum path length, is used to create a pool of viable lines (Oliker & Bekhor, 2020) . In the route configuration step, the lines and frequencies are set using this pool of lines and passenger demand to maximise the objectives while working within the constraints (Durán-Micco & Vansteenwegen, 2022a). This can be done with a wide variety of types of analytical models, mathematical programming or heuristic or metaheuristics methods, usually in iterative fashion (Kepaptsoglou & Karlaftis, 2009). Finally, the passenger assignment subproblem involves modelling the decisions passengers take to go from their origin to their destination on a given transit network. This results in loads and line usage which can be used to evaluate the performance of the lines and thus directly influences operator decision making (Durán-Micco & Vansteenwegen, 2022a). It is a crucial step of the method, as even in its simplest form it is the most time-consuming part when it comes to solving the problem (Farahani et al., 2013).

TNDFSP methods are rarely used in the actual design of real transit networks, instead using real case study data to generate realistic instances or

validate results (Durán-Micco & Vansteenwegen, 2022a). The vast majority of these case studies are done on urban bus networks of various sizes and less so on other modes. Notable exceptions to this for rail include Liu et al. (2020) with a profit-maximising operator on the Chinese High-Speed railway network, Hartleb et al. (2021) applying a mixed-integer linear programming (MILP) formulation on the Dutch rail network, and finally, Grolle et al. (2024) using a TNDFSP framework on the European HSR-network for different economic and investment scenarios, including multimodal competition with road and air.

Previous network and frequency setting literature has mostly focused on optimising networks for a single planner or operator, sometimes including multimodal competition as a fixed external parameter. Competition models have so far been applied to single lines or small corridors, so no study was found which, to the authors' knowledge, combines line planning and frequency setting on a multi-stop rail network, several competing profit-maximising operators and passenger assignment with transfers on a continental network. This paper proposes an adaptation of the TNDFSP that includes the strategic interaction of multiple operators competing for demand on the network.

3. Methodology

The workflow follows the usual structure of TNDFSP approaches. First, a pool of viable lines is created from the infrastructure network and the demand matrix (line generation). Second, starting from an initial line and frequency plan, an iterative line configuration procedure combines the decisions of the operators with a passenger assignment. The resulting network is then evaluated with network, passenger and operator KPIs.

2.4. Network Representation

The network is an undirected graph G = (N, E) with nodes N (cities) and edges E (rail infrastructure). A line $l \in \boldsymbol{L}$ is a sequence of directly connected nodes, and a service is a line operated by a specific operator $s \in \mathbf{S}$. To represent passenger paths across lines and operators, the graph is extended following Heyken Soares (2020): nodes used by several services are duplicated, and transfer edges are added with weight βn for transfers between services of the same operator and βn + βns for transfers between services of different operators. Passengers travel along paths in this extended graph.

2.5. Line Generation Procedure

Following previous work (Filgueiras et al., 2023; Grolle et al., 2024; Mahdavi Moghaddam et al., 2019), a pool of viable lines is generated, balancing solution quality against pool size. The algorithm of Kiliç & Gök (2014), extended by Heyken Soares et al. (2019) and adapted by Grolle et al. (2024), converts the demand assigned to each edge into edge weights (heavily used edges get low weights) and computes the shortest paths between all node pairs with demand using these weights (Figure 1). The resulting lines are filtered to improve quality

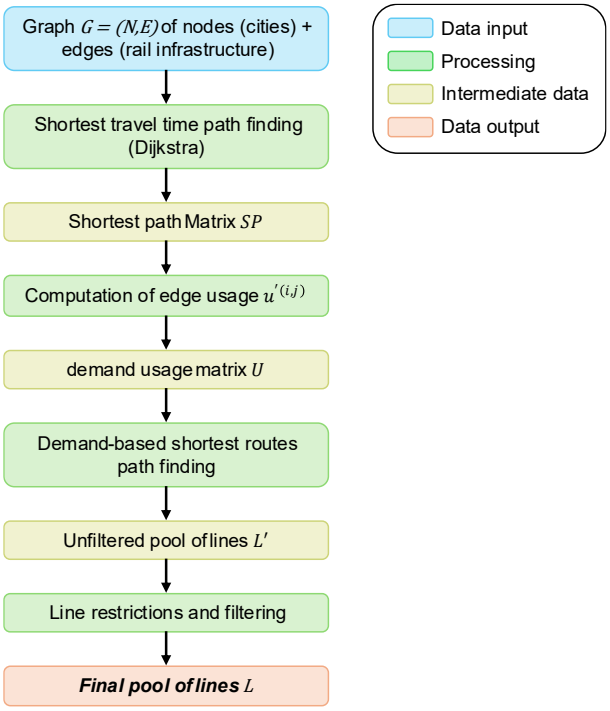


Figure 1: Flowchart of line generation procedure

and realism and to reduce computation: lines need a minimum and a maximum number of stations, a maximum one-directional travel time and a maximum detour factor relative to the shortest path on the infrastructure.

2.6. Line Configuration Procedure

The line configuration step is an iterative algorithm in which every operator strategically selects lines from the pool and sets their frequencies (Figure 2). Each operator solves a mixed-integer linear program (MILP) that maximises its own profit, taking the line and frequency plans of its competitors from the previous iteration as exogenous. The decisions of all operators are merged into a new network plan, to which passengers are assigned, after which demand is updated and the next iteration starts. The process ends when an ε-equilibrium is reached (see the stopping criteria below), which makes the procedure an iterated non-cooperative game with simultaneous, myopic decisions.

2.6.1. Demand assignment

For each OD pair, a set of attractive routes R_{ij} is determined with a k-shortest-path method on the extended graph, keeping only loop-free routes within 20% of the shortest generalised journey time (GJT) (Durán-Micco & Vansteenwegen, 2022). The GJT of a route r is the in-vehicle time plus a penalty βn per transfer and an additional penalty βns for each transfer that involves a change of operator:

$$GJT_r = t_r^t + \beta^n \cdot n_r + \beta^{ns} \cdot ns_r \qquad (5)$$

Passengers are distributed over the routes with a multinomial logit model, where the utility depends on the GJT and on the logarithm of the lowest service frequency on the route (Adler et al., 2010; Cats et al., 2017):

$$v_r = \beta^{GJT} \cdot GJT_r + \beta^f \cdot \ln \min_{l \in r}(f_{sl}) \qquad (6)$$

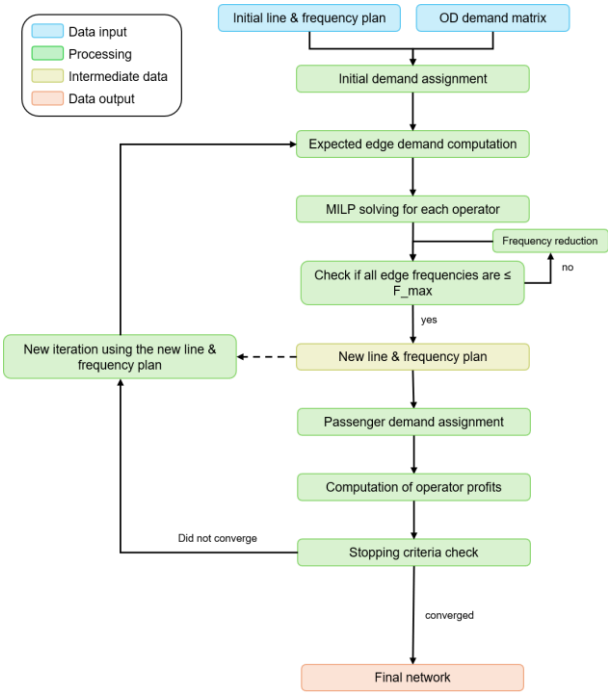


Figure 2: Flowchart of line configuration procedure

The probability that a route r is chosen is then:

$$P_r = \frac{\exp(v_r)}{\sum_{r \in R_{i,j}} \exp(v_r)} \qquad (7)$$

The demand on each service-edge is obtained by multiplying the OD demand with the choice probabilities of the routes that use the edge and summing over all OD pairs. Capacity is enforced by scaling the demand of every route down by the highest saturation (demand divided by seat capacity times frequency) among the service-edges on the route whenever this exceeds one. Demand rejected in this way is not reassigned to other routes and is counted as unserved.

2.6.2. Expected demand

A full passenger assignment for every candidate network is computationally infeasible, so each operator uses an approximation of the expected demand per service-edge based on the previous iteration. For service-edges that are already

operated, this is the demand assigned in the previous iteration. For edges that are not in the network, the origin–destination-based betweenness centrality (Puzis et al., 2013), computed on the unserved demand, estimates the potential demand. For lines that are not yet operated but run parallel to operated services, the average demand of the parallel services is used, and for lines that would create a direct connection more than 20% faster than the current best connection of an OD pair, the demand of that OD pair is added. The approximation does not account for how demand would be split between operators and tends to overestimate the demand of new services (see Section 6).

2.6.3. Demand elasticity

At the end of each iteration, demand is updated to reflect the level of service. Following Guan et al. (2026), the demand is split into a core part that always uses rail when it is available and a variable part that responds to changes in GJT and frequency relative to a base state, using elasticities from the literature (Yap et al., 2018):

$$d_{ij}^{\delta} = d_{ij}^{\delta_0}\left(\varepsilon_{GJT}\left(\frac{GJT^{\delta}}{GJT^{\delta_0}}-1\right)+\varepsilon_f\left(\frac{f^{\delta}}{f^{\delta_0}}-1\right)+1\right) \quad (11)$$

where d, GJT and f are the demand, generalised journey time and frequency in iteration δ and in the base state δ0, and εGJT and εf are the elasticities with respect to GJT and frequency.

2.6.4. Line and frequency setting using a Mixed-Integer Linear Program

Each operator s ∈ S solves the following MILP, given the previous network state and the expected demand. The decision variables are the line selection x_{sl}, the line frequency f_{sl} and the serviced demand on each line-edge $d_{esl}^{serviced}$. The parameters are the entry cost kentry, the operating cost per train-kilometre koperation, the seat capacity cap, the revenue r per passenger-kilometre, the edge lengths c, the maximum edge frequency Fmax, the operator budget bs, the expected demand dtotal, the previous frequencies fprev of the competitors and the previous selection xprev. Each operator can only choose from the viable lines Lsviable, which share at least one node with its current network.

For each operator $s \in S$:

$$\max \sum_{l\in L^{viable}} \sum_{e\in E} d_{esl}^{serviced} \cdot c_e^{edge} \cdot r - (k_l^{entry} \cdot z_{sl} + f_{sl} \cdot c_l^{line} \cdot k^{op}) \quad (12)$$

$$d_{esl}^{serviced} \le f_{sl} \cdot cap \qquad \forall\, e \in E, l \in L_s^{viable} \quad (13)$$

$$d_{esl}^{serviced} \le d_{esl}^{expected} \qquad \forall\, e \in E, l \in L_s^{viable} \quad (14)$$

$$\sum_{l\in L} a_{el} \cdot (f_{sl} + f_l^{prev}) \le F^{max} \qquad \forall\, e \in E \quad (15)$$

$$\sum_{l\in L^{viable}} (k_l^{entry} \cdot z_{sl} + f_{sl} \cdot c_l^{line} \cdot k^{op}) \le b_s \quad (16)$$

$$f_{sl} \le F^{max} \cdot x_{sl} \qquad \forall\, l \in L_s^{viable} \quad (17)$$

$$f_{sl} \ge x_{sl} \qquad \forall\, l \in L_s^{viable} \quad (18)$$

$$z_{sl} \ge x_{sl} - x_{sl}^{prev} \qquad \forall\, l \in L_s^{viable} \quad (19)$$

$$x_{sl} \geq 0 \qquad \forall\, s \in S^{national}, l \in L_s^{initial} \tag{20}$$

$$z_{sl} \geq 0 \qquad \forall\, l \in L \tag{21}$$

$$f_{sl} \in \mathbb{Z}_{\geq 0} \qquad \forall\, l \in L \tag{22}$$

$$x_{sl} \in \{0,1\} \qquad \forall\, l \in L \tag{23}$$

$$d_{esl}^{serviced} \in \mathbb{R}_{\geq 0} \qquad \forall\, e \in E, l \in L \tag{24}$$

Equation (12) is the objective function maximing revenue (r per passenger-kilometre served) minus the entry cost of newly opened lines and the operating cost per train-kilometre. Constraints (13) and (14) limit the serviced demand on a line-edge to the available seat capacity and to the expected demand, and (15) limits the number of trains per edge to the infrastructure capacity F_{max}, taking the previous frequencies of the competitors into account. (16) is the budget constraint on entry and operating costs. (17) and (18) ensure that a line selected must run at least 1 frequency and vice-versa. (19) sets z to 1 for newly opened lines, so that deselecting a line does not give a refund of its entry cost, and (20) requires national operators to keep at least one daily train on every line of their initial network. (21) to (24) are the value constraints for the remaining decision variables.

The frequencies of all operators are merged into a new global line and frequency plan, which is the input of the next passenger assignment.

2.6.5. Frequency reduction and stopping criteria

Because operators decide simultaneously, the edge capacity constraint of F^{max}(15) can be violated in the merged plan. In that case the frequencies on the affected edge are reduced by one train at a time, starting with the highest-frequency service, until the constraint holds. The procedure stops when (i) the maximum of 50 iterations is reached, which indicates that no equilibrium was found, (ii) the objective value of every operator changes by less than 1% between two consecutive iterations (Li et al., 2026), or (iii) the network is identical in two consecutive iterations. The final plan is evaluated with network-wide KPIs.



Figure 3: initial network line map

4. Case study of the 2050 European Rail Network

The case study uses the network and demand data of Grolle et al. (2024), who adapt them from Donners (2016): 123 cities as nodes (Ankara is removed from the 124 cities of the source data because all of its demand lies beyond the 1 500 km range) and 256 edges based on the Trans-European Transport Network (TEN-T). All infrastructure is assumed to be high-speed rail with speeds up to 275 km/h. The demand ends up with 2 838 OD pairs with non-zero daily rail demand. Line generation yields a pool of 1 170 lines. Parameter values (Table

3) are taken from the literature where possible; the entry cost (€70,000) and the operator budgets are modelling parameters chosen for computational reasons and are analysed in a sensitivity analysis.

2.7. Experimental setup

Experiment 1 is the baseline with 14 operators: 11 national operators (A–K) are all assigned to a region and starting from an initial network on which they must keep at least one daily train per line, and 3 private operators (X–Z) that can freely select lines. Every operator has a daily budget bs for entry and operating costs; for national operators it equals the operating cost of their initial network at 12 trains per day plus a quarter of the passenger revenue on it, and for private operators it is set between €0.8M and €1.7M. The inter-operator transfer penalty is βns = 15 minutes. Experiments 2 and 3 represent high coordination (β_{ns} = 0) and low coordination (β_{ns}= 60). Experiments 4 and 5 replace the 14 operators by a single centralised operator that must serve all nodes and starts without an initial network. In experiment 4 it maximises profit and in experiment 5 its objective is replaced by equation (22), maximising the serviced demand only.

$$\max \sum_{l \in L^{viable}} \sum_{e \in E} d_{esl}^{serviced} \qquad (22)$$

These scenarios give insight into how the network differs with and without competition. Sensitivity analyses are performed on the entry cost kentry and on the initial frequency used to compute the national operators' budgets.

The initial network is shown in Figure 3, with operators A–K national and X–Z private. The full input values are given in Appendix 1.

The model is written in Python 3.13.12. Everything was run on a personal laptop with an Intel Core i7-13620H processor (2.40 GHz) and 16 GB of RAM. Running times varied between 20 and 180 minutes depending on the experiment.

5. Results

For the baseline scenario, the model converges after 15 iterations. Operators concentrate their lines in Western Europe, especially on the connections between the UK, France, Belgium, the Netherlands and Germany (Figure 4), with the highest frequency on the edge London–Lille (78 trains per direction per day). 196 of the 256 edges are used, and 169 of the 1 170 lines in the pool are selected and run as 231 services. Many operators run overlapping, long, cross-border services (on average 850 km) with low individual frequencies; nearly 60% of the services run once per day and direction. In the high-demand areas these services bundle into corridors with a

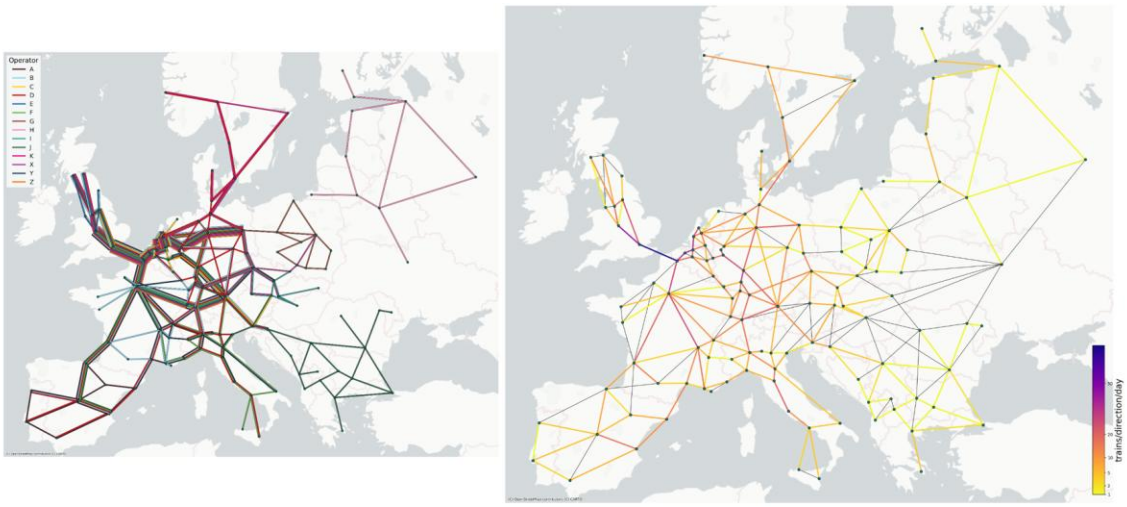


Figure 4: line map (left) and edge-frequency map (right) of baseline scenario network.

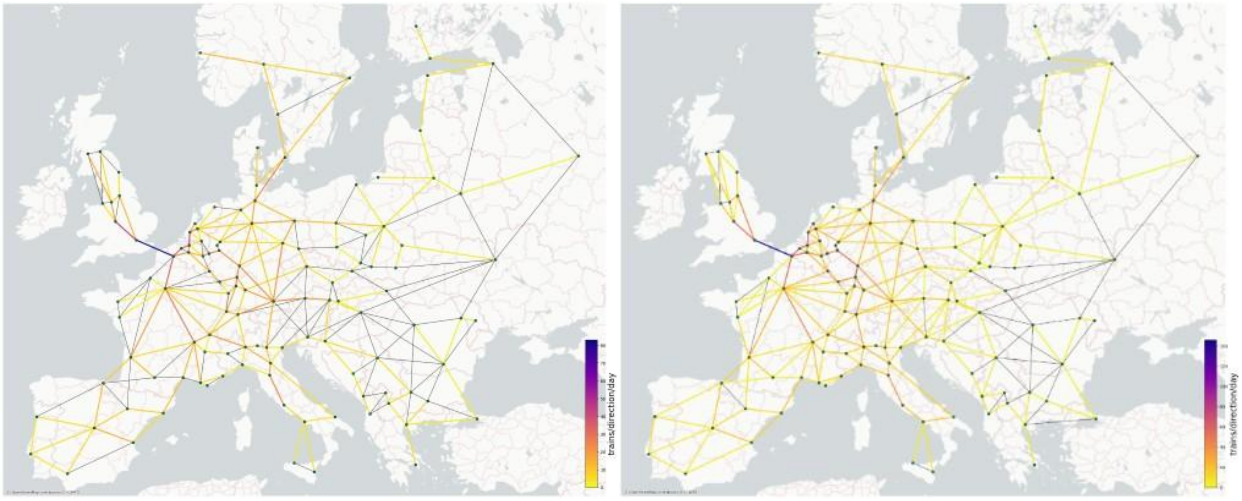


Figure 5: edge frequency of centralised operator with profit-maximisation (left) and demand-maximisation (right)

high total frequency, a diversity of operators and many direct connections. The north-eastern part of the network (Russia, the Baltics, Finland, Ukraine) remains isolated, and the Balkans are connected to the rest only through Ljubljana (2,747 of the 2,838 OD pairs with demand are reachable). About 76% of the demand is served, 65% of it without a transfer and about 91% with at most one transfer. Part of the unserved demand results from the isolation of the north-east and from capacity-rejected demand that is not reassigned. The first three experiments lead to similar networks (Table 1).

Table 1: KPIs of the first three experiments (coordination scenarios)

	Unit	Baseline	High coordination	Low coordination
Number of active lines	[-]	169	163	163
Number of active services	[-]	231	274	244
Number of used edges	[-]	196	198	192
Number of reachable ODs	[-]	2 747	2 747	2 747
Train-kms	[10^3 km]	712.67	760.13	722.24
Average stops per line	[-]	4.31	4.40	4.35
Average stops per service	[-]	4.73	4.85	4.75
Average line length	[km]	783	788	775
Average service length	[km]	849	872	857
Network connectivity	[-]	0.540	0.545	0.529
Unserved passenger demand	[pax] & [%]	98 599 (23.76%)	106 450 (24.76%)	96 529 (23.33%)
Served passenger demand	[pax] & [%]	316 388 (76.24%)	323 452 (75.24%)	317 282 (76.67%)
Served passengers, 0 transfers (% of served)	[pax] & [%]	206 104 (65.14%)	212 886 (65.82%)	206 296 (65.02%)
Served passengers, 1 transfer (% of served)	[pax] & [%]	82 624 (26.11%)	87 424 (27.03%)	80 242 (25.29%)
Served passengers, 2 transfers (% of served)	[pax] & [%]	22 740 (7.19%)	19 385 (5.99%)	23 705 (7.47%)
Served passengers, 3+ transfers (% of served)	[pax] & [%]	4 919 (1.55%)	3 756 (1.16%)	7 040 (2.22%)
Passenger-kms	[10^6 km]	195.22	197.74	196.70
Average travel distance per passenger	[km]	617.03	611.33	619.96
Average travel time per passenger	[min]	205.80	202.08	207.83
Total profit of all operators	[10^3 €/day]	9 855.25	8 833.91	9 804.98

Removing the transfer barrier between operators (βns = 0) leads to more services (274 against 231) and 6.7% more train-kilometres. The absolute demand served increases by 2.2% (total demand by 3.6% through induced demand) and the average travel time falls by 1.8%, but the share of demand served decreases slightly (75.2% against 76.2%) and the total profit of all operators falls by about 10% (from €9.86M to €8.83M per day). The scenario with a high barrier (βns = 60) is close to the baseline (76.7% served, total profit €9.80M). Operators A, E and J gain from high coordination, whereas B, D, F, G and I lose, and B and G do best with low coordination (Appendix 2). The differences between the three scenarios are small (1–3% for most KPIs) and have not been tested for run-to-run variability.

A single profit-maximising operator (experiment 4) produces a network with a similar distribution of edge frequencies (Figure 5) but fewer edges (169 against 196), longer lines, lower connectivity (0.466 against 0.540) and a lower share of demand served than the competing operators (72.1% against 76.2%, Table 2). Its profit (€8.80M per day) is not higher than the sum of the profits of the competing operators (€9.86M), although a single operator could in principle replicate their combined plans, which points to limitations of the demand expectation and the budget rather than to an economic effect. The demand-maximising operator (experiment 5) selects 575 lines on 222 edges, serves 98.0% of the demand (22 percentage points more than the baseline) with 39% more passenger-kilometres, but at a profit margin of about 6% (€2.5M profit on €43.5M revenue per day) and with about twice the train-kilometres.

The sensitivity analyses show that the entry cost has a sizeable effect: with k^{entry} of €25 000 or less the model does not converge within 50 iterations and oscillates between network states, whereas higher values reduce the number of services and increase the dependence on the initial networks. The

Table 2: KPIs of the baseline and the centralised operator scenarios (experiments 4 and 5)

	Unit	Baseline (competition)	Central operator: profit max. (exp. 4)	Central operator: demand max. (exp. 5)
Number of active lines	[-]	169	159	575
Number of active services	[-]	231	159	575
Number of used edges	[-]	196	169	222
Number of reachable ODs	[-]	2 747	2 838	2 838
Train-kms	[10^3 km]	712.67	732.56	2 516.73
Average stops per line	[-]	4.31	5.05	5.38
Average stops per service	[-]	4.73	5.05	5.38
Average line length	[km]	783	925	900
Average service length	[km]	849	925	900
Network connectivity	[-]	0.540	0.466	0.612
Unserved passenger demand	[pax] & [%]	98 599 (23.76%)	117 968 (27.94%)	8 741 (1.97%)
Served passenger demand	[pax] & [%]	316 388 (76.24%)	304 282 (72.06%)	434 011 (98.03%)
Served passengers, 0 transfers (% of served)	[pax] & [%]	206 104 (65.14%)	198 736 (65.31%)	321 197 (74.00%)
Served passengers, 1 transfer (% of served)	[pax] & [%]	82 624 (26.11%)	81 295 (26.72%)	98 604 (22.72%)
Served passengers, 2 transfers (% of served)	[pax] & [%]	22 740 (7.19%)	19 627 (6.45%)	13 158 (3.03%)
Served passengers, 3+ transfers (% of served)	[pax] & [%]	4 919 (1.55%)	4 624 (1.52%)	1 051 (0.24%)
Passenger-kms	[10^6 km]	195.22	192.34	271.77
Average travel distance per passenger	[km]	617.03	632.12	626.17
Average travel time per passenger	[min]	205.80	209.24	204.08
Profit	[10^3 €/day]	9855.25	8 797.84	2 516.73
Load factor	[%]	68.5	65.64	49.75

budgets, varied through the initial frequency (3 to 18 trains per day), do not lead to consistent changes in the KPIs, so the budget does not appear to be binding in most cases.

6. Conclusion and Discussions

Within the assumptions of the model, competition between profit-seeking operators leads to a dense and diversified service in corridors with sufficiently high demand: many overlapping long-distance services that give most passengers a direct connection (65% of the served demand), which is consistent with the more diverse supply found in empirical case studies (Bergantino et al., 2015; Tomeš et al., 2016; Vigren, 2017). However, the model does not reproduce the empirical finding that competition increases total supply: a single profit-maximising operator runs a similar number of train-kilometres on a network with a similar structure. The concentration on high-demand areas and the minimal service in Eastern and peripheral regions therefore follow mainly from profit maximisation and not from competition as such. This is consistent with warnings in the literature that unprofitable lines are at risk (Bergantino et al., 2015; Moyano & Dobruszkes, 2025; Steer Davies Gleave, 2016), although the model does not represent cross-subsidisation between lines, and the minimum service that remains in low-demand regions is partly imposed by the obligation of national operators to keep their initial lines.

Reducing the barriers to transfers between operators slightly increases the absolute demand served and shortens travel times, but lowers the share of demand served and operator profits, and a high barrier makes little difference. Because coordination is represented only by a transfer penalty and the effects are small, no conclusion on the value of ticketing or timetable integration should be drawn beyond the direction of the effect. Compared with a centralised planner, only the operator that maximises served demand clearly outperforms competition for passengers (98% against 76% served), at a much lower profit margin (6% against 32%) and without accounting for infrastructure costs; the profit-maximising central operator is not better than competition. The objective of the operator therefore matters more than the market structure. Two implications for the liberalisation of European passenger rail follow, subject to the limitations below. First, a central or public planner with a service objective can serve passengers better than competing profit-seeking operators, but such a structure is unlikely given the political structure of the EU, its sovereign states and the non-EU countries that are central to this network (such as the UK and Switzerland); alternatives such as public service obligations or tendering of peripheral lines were not tested. Second, low-demand areas are left at close to minimum service when operators are driven by profit, so liberalisation may need to be accompanied by subsidies or service obligations to prevent growing regional inequalities. The subsidy needs were not quantified, and part of the lowest-served area lies outside the EU.

The results should be interpreted as indicative. Prices and service differentiation are not modelled, and there is no fixed cost per service. The expected-demand approximation ignores the demand split between operators and likely overestimates the demand of new services, which contributes to the many low-frequency services and to oscillation at low entry costs. The passenger assignment treats overlapping services as independent alternatives, does not reassign demand rejected by capacity and scales poorly. The market structure (14 operators), the budgets and the entry cost are exogenous modelling choices, each scenario was run once so that small differences cannot be distinguished from run-to-run variation, and the model was not validated against observed services. Finally, the interoperability of the network is idealised: all edges are high-speed and operators are assumed to run

across borders without technical or regulatory barriers.

Future research should (1) improve the expected-demand and update mechanism, for example with explicit demand sharing between operators, damped or sequential best responses and an explicit test of the equilibrium; (2) refine the MILP with a fixed cost per service, a consistent time basis for the entry cost and fleet or investment limits, and add robustness tests with several initial networks and a broader sensitivity analysis; (3) extend the outcomes with welfare, subsidy and emission measures and with competing modes; (4) model the market structure endogenously and give public and private operators different objectives (Ristić et al., 2022); and (5) include pricing, at least on smaller instances (Álvarez-SanJaime et al., 2015; Cherbonnier et al., 2018). For larger networks, heuristic solution methods and a more efficient demand assignment are needed, as exact TNDFSP methods are hard to scale (Owais, 2026).

References

Adler, N., Pels, E., & Nash, C. (2010). High-speed rail and air transport competition: Game engineering as tool for cost-benefit analysis. *Transportation Research Part B: Methodological*, *44*(7), 812–833. https://doi.org/10.1016/j.trb.2010.01.001

Álvarez-SanJaime, Ó., Cantos-Sanchez, P., Moner-Colonques, R., & Sempere-Monerris, J. J. (2015). A model of internal and external competition in a High Speed Rail line. *Economics of Transportation*, *4*(3), 178–187. https://doi.org/10.1016/j.ecotra.2015.05.004

Álvarez-SanJaime, Ó., Cantos-Sanchez, P., Moner-Colonques, R., & Sempere-Monerris, J. J. (2016). Rail access charges and internal competition in high speed trains. *Transport Policy*, *49*, 184–195. https://doi.org/10.1016/j.tranpol.2016.04.006

Antoniazzi, F., Giuricin, A., & Tosatti, R. (2020). Introducing competition in Italian high-speed rail. *L'Espace Géographique*, *Tome 48*(4), 329–349. https://doi.org/10.3917/eg.484.0329

Battilocchi, T., Beria, P., & Pařil, V. (2026). The third phase of the liberalisation of European long-distance passenger railways. *European Transport Studies*, *3*. https://doi.org/10.1016/j.ets.2026.100067

Behrens, C., & Pels, E. (2012). Intermodal competition in the London-Paris passenger market: High-Speed Rail and air transport. *Journal of Urban Economics*, *71*(3), 278–288. https://doi.org/10.1016/j.jue.2011.12.005

Bergantino, A. S., Capozza, C., & Capurso, M. (2015). The impact of open access on intra- and inter-modal rail competition. A national level analysis in Italy. *Transport Policy*, *39*, 77–86. https://doi.org/10.1016/j.tranpol.2015.01.008

Broman, E., & Eliasson, J. (2019). Welfare effects of open access competition on railway markets. *Transportation Research Part A: Policy and Practice*, *129*, 72–91. https://doi.org/10.1016/j.tra.2019.07.005

Cascetta, E., & Coppola, P. (2014). Competition on Fast Track: An Analysis of the First Competitive Market for HSR Services. *Procedia - Social and Behavioral Sciences*, *111*, 176–185. https://doi.org/10.1016/j.sbspro.2014.01.050

Cats, O. (2025). The long journey towards a shift to rail in the European long-distance passenger transport market. *Npj Sustainable Mobility and Transport*, *2*(1). https://doi.org/10.1038/s44333-025-00025-9

Cats, O., Koppenol, G. J., & Warnier, M. (2017). Robustness assessment of link capacity reduction for complex networks: Application for public transport systems. *Reliability Engineering and System Safety*, *167*, 544–553. https://doi.org/10.1016/j.ress.2017.07.009

Cherbonnier, F., Ivaldi, M., Muller-Vibes, C., Van, K., & Straeten, D. (2018). *Competition For Versus In the Market of Long-Distance Passenger Rail Services*.

de Rose, A., Trier Jørgensen, K., & Doklestic, N. (2024). *Study on passenger and freight rail transport services' prices for final customers Final Report*. https://op.europa.eu/publication-detail/-/publication/4ea76998-7955-11ef-bbbe-01aa75ed71a1

Desmaris, C., & Croccolo, F. (2018). The HSR competition in Italy: How are the regulatory design and practices concerned? *Research in Transportation Economics*, *69*, 290–299. https://doi.org/10.1016/j.retrec.2018.05.004

Donners, B. (2016). *Erasing borders European Rail Passenger Potential*. Delft University of Technology.

Durán-Micco, J., & Vansteenwegen, P. (2022). Transit network design considering link capacities. *Transport Policy*, *127*, 148–157. https://doi.org/10.1016/j.tranpol.2022.08.018

European Commission. (2025). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Connecting Europe through High-Speed Rail*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52025DC0903

Filgueiras, M., Gkiotsalitis, K., Yap, M., Cats, O., Lobo, A., & Ferreira, S. (2023). Bus Network Design and Frequency Setting in the Post-COVID-19 Pandemic: The Case of London. *Journal of Transportation Engineering, Part A: Systems*, *149*(4). https://doi.org/10.1061/jtepbs.teeng-7176

Grolle, J., Donners, B., Annema, J. A., Duinkerken, M., & Cats, O. (2024). Service design and frequency setting for the European high-speed rail network. *Transportation Research Part A: Policy and Practice*, *179*. https://doi.org/10.1016/j.tra.2023.103906

Guan, H., Basciftci, B., & Van Hentenryck, P. (2026). *Bilevel Optimization and Heuristic Algorithms for Integrating Latent Demand into the Design of Large-Scale Transit Systems*. https://doi.org/10.1287/trsc.2025.0194

Heyken Soares, P. (2020). *Three Steps Towards Practical Application of Public Transport Route Optimisation in Urban Areas* [Doctoral Dissertation, University of Nottingham]. https://doi.org/DOI:10.13140/RG.2.2.24062.20802

Kiliç, F., & Gök, M. (2014). A demand based route generation algorithm for public transit network design. *Computers & Operations Research*, (51), 21–29. https://doi.org/DOI:10.1016/j.cor.2014.05.001

Kvizda, M., & Solnička, J. (2019). Open access passenger rail competition in Slovakia – Experience from the Bratislava–Košice line. *Journal of Rail Transport Planning and Management*, *12*. https://doi.org/10.1016/j.jrtpm.2019.100143

Laroche, F., & Lamatkhanova, A. (2022). Effects of open access competition on prices and frequencies on the interurban railway market: Evidence from Europe. *Research in Transportation Business and Management*, *43*. https://doi.org/10.1016/j.rtbm.2021.100705

Li, M., Birolini, S., & Ribeiro, N. A. (2026). Hub competition and demand modeling in long-haul aviation markets: A forward-looking scenario-based game-theoretical approach. *Transportation Research Part E: Logistics and Transportation Review*, *211*. https://doi.org/10.1016/j.tre.2026.104894

Mahdavi Moghaddam, S. M. H., Rao, K. R., Tiwari, G., & Biyani, P. (2019). Simultaneous Bus Transit Route Network and Frequency Setting Search Algorithm. *Journal of Transportation Engineering, Part A: Systems*, *145*(4). https://doi.org/10.1061/jtepbs.0000229

Moyano, A., & Dobruszkes, F. (2025). Privatising profits and socialising losses: The effects of liberalisation on the incumbent high-speed rail operator in Spain. *Research in Transportation Business and Management*, *60*. https://doi.org/10.1016/j.rtbm.2025.101317

Owais, M. (2026). Transit network design problem: a half century of methodological research. *Innovative Infrastructure Solutions*, *11*(1). https://doi.org/10.1007/s41062-025-02356-5

Puzis, R., Altshuler, Y., Elovici, Y., Bekhor, S., Shiftan, Y., & Pentland, A. (2013). Augmented betweenness centrality for environmentally aware traffic monitoring in transportation networks. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*, *17*(1), 91–105. https://doi.org/10.1080/15472450.2012.716663

Railway Gazette International. (2026, August 7). FS Group orders high speed trains for Trenitalia's London – Paris service. *Railway Gazette International* . https://www.railwaygazette.com/rolling-stock/2026/08/07/trenitalia-orders-high-speed-trains-for-london-paris-service/

Ristić, B., Stojadinović, N., & Trifunović, D. (2022). Conditions for effective on-track competition in the European passenger railway market: A yardstick for regulations. *Transport Policy*, *119*, 1–15. https://doi.org/10.1016/j.tranpol.2022.02.006

Steer Davies Gleave. (2016). *Study on the prices and quality of rail passenger services*. www.steerdaviesgleave.com

Stone, J. (2026, August 25). Trains between Britain and Europe on track to run every 15 minutes . *Politico*. https://www.politico.eu/article/train-eurotunnel-britain-europe-every-fifteen-minutes/

Tomeš, Z., & Jandová, M. (2018). Open access passenger rail services in Central Europe. *Research in Transportation Economics*, *72*, 74–81. https://doi.org/10.1016/j.retrec.2018.10.002

Tomeš, Z., Kvizda, M., Jandová, M., & Rederer, V. (2016). Open access passenger rail competition in the Czech

Republic. *Transport Policy*, *47*, 203–211. https://doi.org/10.1016/j.tranpol.2016.02.003

Tomeš, Z., Kvizda, M., Nigrin, T., & Seidenglanz, D. (2014). Competition in the railway passenger market in the Czech Republic. *Research in Transportation Economics*, *48*, 270–276. https://doi.org/10.1016/j.retrec.2014.09.052

Vigren, A. (2017). Competition in Swedish passenger railway: Entry in an open access market and its effect on prices. *Economics of Transportation*, *11–12*, 49–59. https://doi.org/10.1016/j.ecotra.2017.10.005

Yap, M. D., Nijënstein, S., & van Oort, N. (2018). Improving predictions of public transport usage during disturbances based on smart card data. *Transport Policy*, *61*, 84–95. https://doi.org/10.1016/j.tranpol.2017.10.010

Appendix 1. Parameter values

Table 3: Parameter values

Name	Value
t^{stop}	$4\ mins$
γ	1.05
st^{min}	$3\ stops$
st^{max}	$12\ stops$
TT^{max}	$480\ mins$
det	1.5
cap	$400\ pax$
r	$0.16\ €/pkm$
F^{max}	$216\ trains/direction/day$
k^{op}	$30\ €/train\ km$
k^{entry}	70 000 €
β^{GJT}	-0.02
β^{n}	$30\ mins$
β^{ns}	$15\ mins$
β^{f}	0.9
α	0.5
GJT^{δ_0}	$2 \cdot GJT^{SP}$
f^{δ_0}	18
ε_{GJT}	-0.85
ε_{f}	0.15