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Abstract (English)

This thesis develops and analyses a comprehensive optimization framework for the railway Line Planning Problem (LPP) in a large-scale, international context. The study investigates how different objective formulations influence the structure, performance, and economic viability of passenger rail line plans. Three single-objective linear programming models are implemented to minimize total travel time, minimize operated distance, and maximize profit. These models generate highly divergent network configurations, ranging from compact regional route structures with limited economic output to long-distance international corridors yielding substantial profitability. To better capture the inherent trade-offs in railway planning, a multi-objective extension is introduced using both a weighted-sum approach and an extensive Pareto-based analysis. These methods produce a spectrum of compromise solutions, illustrating how moderate adjustments in objective weights can shift the network from profit-driven extremes toward more balanced designs with improved operational efficiency.

The empirical results demonstrate that the pure profit-maximizing model strongly favours a small set of long-haul, high-demand international corridors, while the time- and distance-minimizing models produce short, regionally concentrated networks with lower overall performance. The multi-objective models reconcile these extremes by selecting shorter variants of the profitable international routes, thereby enhancing travel efficiency without sacrificing the core economic advantages. The Pareto-based analysis further reveals multiple structurally distinct yet efficient line plans, enabling planners to explicitly evaluate trade-offs between profit, travel time, and distance.

The thesis concludes by proposing a Decision Support System (DSS) that integrates data management, model configuration, scenario exploration, and multi-criteria analysis to support strategic railway planning. Several limitations are acknowledged, including simplified demand assumptions and the absence of timetabling constraints, and directions for future research are outlined. Overall, the study demonstrates the value of multi-objective optimization in guiding railway line planning decisions and provides a robust methodological foundation for designing efficient and economically sustainable rail networks.

Abstract (Deutsch)

Diese Masterarbeit entwickelt und analysiert ein umfassendes Optimierungsframework für das Railway Line Planning Problem (LPP) in einem großskaligen, internationalen Kontext. Die Studie untersucht, wie unterschiedliche Zielfunktionsformulierungen die Struktur, Leistungsfähigkeit und wirtschaftliche Tragfähigkeit von Personenverkehrs-Linienkonzepten beeinflussen. Hierzu werden drei Einzelziel-Linearprogrammierungsmodelle implementiert, die jeweils die gesamte Reisezeit minimieren, die betriebene Streckenlänge minimieren bzw. den Gewinn maximieren. Diese Modelle führen zu stark divergierenden Netzkonfigurationen, die von kompakten, regionalen Routenstrukturen mit begrenztem wirtschaftlichem Ertrag bis hin zu internationalen Langstreckenkorridoren mit hoher Profitabilität reichen. Um die inhärenten Zielkonflikte der Eisenbahnlinienplanung besser abzubilden, wird eine multikriterielle Erweiterung eingeführt, die sowohl einen gewichteten Summenansatz als auch eine umfassende Pareto-Analyse umfasst. Diese Methoden erzeugen ein Spektrum von Kompromisslösungen und verdeutlichen, wie bereits moderate Anpassungen der Zielgewichtungen das Netzwerk von stark profitorientierten Extremlösungen hin zu ausgewogeneren Strukturen mit verbesserter operativer Effizienz verschieben können.

Die empirischen Ergebnisse zeigen, dass das rein gewinnmaximierende Modell eine kleine Anzahl von nachfragestarken internationalen Langstreckenkorridoren deutlich bevorzugt, während die zeit- und distanzminimierenden Modelle kurze, regional konzentrierte Netzwerke mit insgesamt geringerer Leistungsfähigkeit hervorbringen. Die multikriteriellen Modelle überbrücken diese Gegensätze, indem sie verkürzte Varianten der profitablen internationalen Routen auswählen und dadurch die Reiseeffizienz erhöhen, ohne die zentralen wirtschaftlichen Vorteile aufzugeben. Die Pareto-basierte Analyse identifiziert darüber hinaus mehrere strukturell unterschiedliche, aber effiziente Linienkonzepte, die es Planern ermöglichen, die Zielkonflikte zwischen Gewinn, Reisezeit und Streckenlänge explizit zu bewerten.

Abschließend schlägt die Arbeit ein Decision Support System (DSS) vor, das Datenmanagement, Modellkonfiguration, Szenarioanalyse und multikriterielle Bewertung integriert, um die strategische Eisenbahnplanung zu unterstützen. Mehrere Einschränkungen werden aufgezeigt, darunter vereinfachte Nachfrageannahmen und das Fehlen von Fahrplanrestriktionen, und es werden Ansätze für zukünftige Forschungsarbeiten skizziert. Insgesamt verdeutlicht die Studie den Mehrwert multikriterieller Optimierung für die Entscheidungsunterstützung in der Eisenbahnlinienplanung und liefert eine robuste methodische Grundlage für die Gestaltung effizienter und wirtschaftlich nachhaltiger Schienennetze.

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1. Introduction

In modern times, the variety and offer of traveling systems has expanded significantly compared to the past. Depending on the distance of your starting point, destination, and wealth, you can choose between faster, more comfortable or more exciting ways of traveling. A popular way is to take a train. This most of the time eco-friendly transportation vehicle has a huge history and have lived through several industrial and technological upswings. In 1825, the first official route was opened for the public. Back then, the high speed of such a train was not nearly as high as that of today's successors. With the modern Inter-City Express Generation, the Deutsche Bahn offers a high-speed train that can operate on up to 320 km/h. This is fascinating, but on the other hand, disappointing because it lives under its potential (Ciccarelli et al., 2021; Putatunda et al., 2019).

As a foreign student based in Würzburg, Germany, and studying in Vienna, it occurs at irregular intervals that I must travel by train between the two locations. Fortunately, there is a convenient long-distance connection operated jointly by Deutsche Bahn AG and Österreichische Bundesbahnen (ÖBB, 2025a), running from Vienna all the way to Dortmund and passing through Würzburg as one of its intermediate stops. Travelling comfortably with the third generation of the Inter-city Express, one has plenty of time to reflect on the journey you have embarked on.

As an ongoing Master of Business Administration graduate, doubts concerning the overall performance of this route rise quickly. If one neglects the elapsed time during a stop and estimates the required time to travel from Vienna to Würzburg, the result is a little more than 2 ½ hours of travel time. Even after accounting for the average stop time of 1–3 minutes and the deceleration and acceleration phases when approaching and leaving a station, the actual travel time appears to be longer than it could be (Heister et al., 2009). From the perspective of line planning, this raises fundamental questions about the balance between travel speed, network coverage, and passenger demand. The railway system connecting Vienna and Dortmund, with Würzburg as an intermediate stop, is part of a dense European network that plays a central role in enabling regional accessibility while linking major economic and academic hubs. Efficient operation of such a line is therefore crucial: on the one hand, frequent stops increase accessibility and improve area coverage, but on the other hand, they reduce average travel speed and extend overall journey times. Optimizing this trade-off is at the core of the line planning problem, where demand patterns, operational efficiency, and service quality must be jointly considered to ensure that the network serves passengers effectively while remaining competitive with other modes of transport.

The strategy and goal regarding this project are thus clear. The problem is called a “Network Problem” at a strategic level of this scenario. The line planning is responsible for the efficiency of the travel route and hence is a direct mediator for the overall profit of the companies. The central idea of this thesis is to design and evaluate an optimization-based framework for long-distance high-speed rail line planning in the context of the heterogeneous, capacity-constrained, and internationally interconnected railway network of Central Europe. Instead of focusing on a single national system or relying on pre-defined line pools, the thesis develops a unified modelling approach that generates optimal long-distance routes across Austria, Germany, and neighbouring countries using a combination of synthetic demand estimation, capacity-aware routing, and economic performance assessment. The core objective is to determine which cross-border high-speed lines could feasibly operate under realistic infrastructure conditions while achieving strong passenger uptake and financial viability.

The thesis makes four main contributions. First, it constructs a continent-scale, empirically grounded rail network from OpenStreetMap infrastructure, converting 117 nodes and thousands

of track segments into a weighted network suitable for optimization. Second, it introduces a revenue-based line planning model that simultaneously considers distance, travel time, passenger demand, route feasibility, and section-level capacity, which allows for evaluating both operational and economic performance of candidate solutions - an aspect often treated separately in existing literature. Third, it proposes a benchmark-based validation framework in which seven real-world long-distance routes are simulated and compared with solver-generated solutions. This approach establishes a transparent method for assessing the plausibility of optimized lines, something rarely done in academic line-planning studies. Fourth, the thesis demonstrates that the model can identify financially superior alternatives to several existing routes, while also revealing structural bottlenecks, capacity shortages, and demand imbalances that must be addressed to ensure operational feasibility.

Overall, the thesis contributes a novel, data-driven methodology for evaluating and designing international high-speed services within complex mixed-traffic networks, bridging the gap between theoretical line-planning models and the practical realities of European railway operations. It provides both a replicable modelling framework and actionable insights into how long-distance rail services could be structured in a future Central European high-speed network.

Topic and Relevance

After quick research, the problem doesn't lie in the limited high speed of the train itself, but in the line planning of the high-speed route. A direct connection does not automatically represent the best or fastest solution; in fact, optimizing for shortest travel time and optimizing for operational efficiency can lead to different service patterns. Line planning determines which trains run on which infrastructure segments, how frequently, and in what stopping pattern. In other words, the line-planning problem is a strategic optimization task in which the goal is to design a set of train lines that best utilise the existing network while satisfying passenger demand and operational constraints. Its main objective is to balance travel time, network capacity, and cost efficiency in a way that maximizes overall system performance. In fact those criterias can result in different lines. Whether you want to be fast or efficient depends which line you choose to be operated on. As mentioned, on the whole route, there are only a couple of sections where the train can operate on its high-speed potential. And those are not covering most of the distance. This gives a huge opportunity for both Companies and creates a big interest in pursuing. By replanning the used lines, the travel time can be reduced significantly, and that means more potential customers will choose to travel via train. On the other hand, more journeys can be made on one day, also increasing the total number of customers and with that the overall revenue. In 2023, long-distance transport was responsible for roughly 20% of the revenue for the Deutsche Bahn AG (DB AG, 2024). In the same year, they estimated together with the ÖBB around 40% more passengers than in the last 5 years before (Heilgenthal, 2023).

Several challenges and problems occur on the way to achieving a fully upgraded high-speed route between Vienna and Würzburg, and researching an entire upgrade scenario while considering every technical, financial, and demand-related aspect would constitute an overly complex and highly uncertain undertaking. Because future demand conditions and the full cost structure of such a project cannot be reliably estimated using existing literature alone, this thesis instead focuses on the line planning problem within the broader Central European railway network, which in this study encompasses 117 cities. The research is carried out across this wider network rather than concentrating on a single city pair, with the objective of identifying efficient train lines or line combinations through an analysis of alternative route structures and train paths. To ensure that the proposed solutions remain realistic and operationally meaningful, they are benchmarked

against major existing high-speed routes in Central Europe, thereby grounding the methodological framework in established performance patterns and competitive standards. This approach allows the thesis to contribute both theoretical insight and practical relevance to contemporary line planning research. Furthermore, the importance and timeliness of this investigation are underscored by the substantial body of prior work on line planning for both high-speed and conventional rail systems, which has informed the development of this study through an accompanying literature review addressing key challenges, methodological advances, and existing solution strategies in the field.

2. Literature Review

Railway line planning constitutes a central strategic decision problem in passenger rail systems, as it determines the set of operated services, their stopping patterns, and frequencies on a given infrastructure. Over the past decades, the literature has evolved from passenger-oriented flow optimization toward increasingly integrated, infrastructure-aware, and robustness-driven formulations. This section reviews the relevant contributions by structuring the literature into five thematic streams and positioning the present thesis within this progression.

Passenger-Oriented Line Planning and Flow Optimization

Early and foundational contributions to the line planning problem primarily focus on optimizing passenger flows and operational costs under a fixed infrastructure assumption. Zhou et al. (2022) investigate the dynamic evolution of railway networks when new lines are integrated, constructing a passenger travel network and proposing an optimization model that explicitly accounts for transportation resource constraints. Their work highlights how merged rail structures alter travel patterns and overall network performance, emphasizing the importance of system-wide passenger interactions rather than isolated line decisions.

Similarly, Wang et al. (2018) propose a two-layer optimization framework that integrates stop schedule design with passenger flow assignment. Their model aims to minimize operating costs while simultaneously reducing unserved passenger demand and is empirically validated using case studies from Taiwan's and China's high-speed rail networks. Both studies illustrate a core strand of the literature in which line planning is primarily evaluated through its ability to efficiently accommodate passenger demand.

Building on this passenger-centric perspective, Song et al. (2021) introduce a nonlinear line planning model that explicitly incorporates service accessibility as an optimization objective alongside operational cost minimization. Accessibility is quantified through indicators capturing spatial coverage, service frequency, directness of travel, and generalized travel effort including travel time and transfer penalties. By embedding these measures directly into the objective function, their work shifts the focus from purely cost-efficient solutions toward passenger-oriented service quality. Wu et al. (2023) further extend this idea by proposing a bilevel daily line planning framework that adapts reference line plans to improve cost efficiency and operational stability, demonstrated on the Beijing–Shanghai high-speed rail corridor.

While these approaches provide valuable insights into passenger demand satisfaction and service design, they largely rely on fixed infrastructure representations and often abstract from detailed operational feasibility constraints.

Increasing Model Realism: Time Dependence, Mixed Traffic, and Demand Uncertainty

As research progressed, scholars began to incorporate additional layers of realism into line planning models. Chen et al. (2024) study a multi-period, mixed-use railway system that jointly accommodates passenger and freight services. Their path-based mixed-integer programming formulation introduces computational strategies to manage interactions between different traffic types, a consideration of particular relevance in European railway systems where freight and passenger trains frequently share infrastructure.

Temporal dynamics further complicate the problem. Hao et al. (2023) address time-dependent passenger demand and overtaking constraints by formulating a mixed-integer nonlinear model that simultaneously optimizes line planning and scheduling decisions. Their objective function minimizes total system costs, including travel time and departure penalties, thereby bringing the formulation closer to real-world operational requirements.

Demand modeling itself constitutes another important dimension. Barzegar Tilenoie et al. (2022) analyze passenger demand forecasting for high-speed rail in markets without direct air travel competition. Although the competitive context differs from that of Central Europe, their survey-based methodology offers transferable insights into passenger behavior and break-even analysis for high-speed rail investments. Collectively, these studies demonstrate how increasing realism in demand representation and traffic interaction significantly raises the complexity of line planning models.

Line Planning in the Context of Infrastructure Constraints

A critical distinguishing feature of European railway systems lies in the intensive sharing of infrastructure among high-speed, regional, and freight services. Unlike Japan's largely segregated high-speed network, countries such as Germany and Austria operate heterogeneous traffic on common tracks, resulting in congestion and punctuality challenges. Meng (2020) explores high-speed express freight operations in China and shows how dedicated infrastructure can improve network performance, indirectly highlighting the structural limitations faced by mixed-use European systems.

A broader planning perspective is provided by Lusby et al. (2009), who review railway planning processes across strategic, tactical, and operational levels, including track allocation, timetabling, and dispatching. Their hierarchical classification situates line planning as a strategic decision that fundamentally constrains downstream operational feasibility. Building on this framework, Fu et al. (2015) propose a hierarchical line planning approach that integrates efficiency metrics such as capacity utilization, travel time, and transfer numbers. Their decision-support-oriented framework enables the derivation of both cost-focused and customer-oriented line plans, linking high-level planning objectives to concrete service configurations.

These contributions underline that line planning cannot be meaningfully separated from infrastructure characteristics, especially in densely utilized European networks.

Beyond Sequential Planning: Integration and Robustness

Recognizing the limitations of traditional sequential planning approaches, a growing body of literature integrates line planning with timetable feasibility and robustness considerations. Yao et al. (2024) depart from the conventional assumption of a predefined line pool and introduce a dynamic line generation approach in which candidate lines are created endogenously within the optimization process. By combining branch-price-and-cut methods with neighborhood search, their model

scales to networks with millions of potential line combinations, as demonstrated on the Shandong high-speed railway network.

Zhang et al. (2022) embed the line planning problem within a unified integer linear programming framework that simultaneously determines line plans and cyclic timetables. By abandoning the traditional strategic–tactical separation, their model ensures that selected line structures and frequencies are inherently compatible with timetable constraints. Similarly, Yan and Goverde (2019) address heterogeneous demand patterns by proposing a multi-frequency line planning model that allows each candidate line to operate with an individually determined frequency, capturing both periodic and aperiodic service characteristics.

Robustness is explicitly addressed by Burggraeve et al. (2017), who demonstrate that cost-efficient line plans may become infeasible once operational timetable constraints are imposed. By iteratively linking a deterministic line planning model with a Periodic Event Scheduling Problem (PESP) formulation, they identify structural infeasibilities arising from route layouts and frequency combinations. Their findings emphasize the importance of detecting timetable infeasibility early in the planning process. Fuchs et al. (2022) further extend this perspective by introducing an infrastructure-aware line planning framework that embeds detailed conflict detection directly into line plan generation, enabling bidirectional feedback between timetable construction and line planning decisions.

The methodological approach developed in this thesis aligns closely with the central themes observed in recent line-planning research while extending them to the specific operational and infrastructural characteristics of the Central European railway network. Whereas Song et al. (2021) and Wu et al. (2023) emphasize accessibility maximization and cost-oriented adjustments in non-linear and bi-level planning models, the present work adopts a similarly demand-sensitive structure but applies it within a static, international long-distance context that reflects Europe’s highly interconnected network. The integration of infrastructural constraints, mixed-traffic operations, and border-crossing requirements corresponds to the challenges identified in studies such as Meng (2020) and complements the optimization-oriented frameworks of Wang et al. (2018) and Hao et al. (2023), which highlight the importance of resource limitations and time-dependent factors. In contrast to highly integrated or joint line–timetable optimization approaches, such as those proposed by Zhang et al. (2022) and Yan and Goverde (2019), this thesis deliberately confines the scope to strategic line planning without generating full cyclic timetables, consistent with its objective of evaluating feasible long-distance services rather than optimizing complete operational schedules. The modelling approach differs further from dynamic line-pool generation methods such as Yao et al. (2024) by relying on a fixed but comprehensive node set derived through empirically constructed network distances, which ensures that the optimization is grounded in real infrastructure and existing corridor geometries. The demand estimation procedure, based on demographic and distance-related indicators, parallels the demand-oriented frameworks of Barzegar Tilenoie et al. (2022), while its integration into a revenue-maximizing objective ensures consistency with the economic evaluation paradigms common in recent literature. Finally, the comparative assessment of the solver-generated routes against seven real benchmark lines reflects the validation logic found in infrastructure-aware planning studies such as Burggraeve et al. (2017) and Fuchs et al. (2022), albeit implemented on a macroscopic level through performance indicators including distance, travel time, capacity utilisation, and profitability. Overall, the approach presented in this thesis situates itself within the established academic discourse while providing a novel contribution through its practical adaptation of line-planning methodologies to the heterogeneous, cross-border, and capacity-constrained conditions of the Central European high-speed rail system.

Positioning of the Present Thesis

Taken together, the literature reveals a clear trade-off between model flexibility, computational tractability, and infrastructure realism. While recent approaches increasingly integrate robustness, timetable feasibility, and dynamic line generation, many models either focus on limited network scales, rely on abstract infrastructure representations, or address single-objective formulations.

The present thesis builds on these advances by focusing on a large-scale Central European railway network and explicitly grounding all candidate lines in existing infrastructure. Rather than generating lines dynamically during optimization, a comprehensive but constrained set of geographically derived and infrastructure-feasible paths is constructed *ex ante*, enabling systematic multi-objective evaluation of line configurations. In doing so, the thesis aims to bridge the gap between passenger-oriented optimization, infrastructure realism, and decision-support applicability, providing a unified framework for analyzing strategic line planning trade-offs under real-world European operating conditions.

The existing literature in the field of high-speed rail and the line planning problem is predominantly centered on the Chinese context. China, with its rapidly developed and expansive high-speed rail network, has been at the forefront of both theoretical and applied research in this domain. However, significant differences exist when comparing the Chinese case to Central Europe. China's railway network has largely been developed in recent decades as a cohesive high-speed system, characterized by newly built infrastructure, standardized rolling stock, and centrally coordinated planning processes. Central Europe, by contrast, is marked by a historically grown railway infrastructure that spans multiple countries, operators, and regulatory frameworks, resulting in a more heterogeneous system where cross-border coordination plays a crucial role.

Despite these differences, the Chinese example offers valuable insights for the scenario investigated in this thesis. Both China and Central Europe share the characteristic of being economically central and highly industrialized regions within their continents, where efficient and competitive railway services are essential for sustainable mobility. Moreover, the existing railway infrastructures in both regions - while different in governance - are comparable in terms of density, connectivity between major metropolitan areas, and the importance of balancing long-distance speed with regional accessibility.

This parallel underlines the relevance of creating a scoped scenario within the Central European area. For railway operators such as Deutsche Bahn (DB) and Österreichische Bundesbahnen (ÖBB), optimizing line planning in such a complex, interconnected network is of strategic importance. Insights derived from adapting approaches commonly studied in the Chinese context to European conditions can therefore contribute to both academic research and practical improvements in cross-border railway operations, efficiency, and competitiveness.

The identified literature is relatively new. On one hand, this makes the relevance kind of more irrelevant, but on the other, this means that real-world examples are at the highest level of comparison as they can be. With that privilege, the significance of the model is high and can create crucial findings for both the Deutsche Bahn and Österreichische Bundesbahnen. Most existing studies focus on Asian high-speed networks, particularly China and Japan. The Central European context - especially cross-border corridors between the European countries - remains underexplored in the literature. Although models like those by Yao et al. (2024) or Meng (2020) consider mixed traffic on either existing or newly created networks, few models are tailored to the operational realities of the Central European network, where freight and passenger trains share tracks. Many studies assume either newly built or fully dedicated high-speed infrastructure. However, the

scenario in question deals with existing rail lines, making it necessary to consider real-world limitations like track capacity, overtaking, and integration with regional services. While Barzegar Tile-noie et al. (2022) introduced demand forecasting via behavioral surveys, no existing models couple this insight with line planning optimization for Central European intercity routes.

Overall, these identified aspects highlight a research gap in the field of high-speed line planning in long-distance passenger rail transportation, particularly for heterogeneous and capacity-constrained networks in Central Europe. To address this gap, this thesis introduces a more narrowly scoped line planning problem that incorporates expanded operational and economic constraints relevant to existing mixed-traffic infrastructure. The proposed mathematical model is explicitly developed by combining core elements of the integrated line planning formulation by Zhang et al. (2022) - which focuses on the strategic selection of feasible train lines under demand satisfaction and capacity considerations - with the path-based and infrastructure-grounded representation of candidate routes found in Yao et al. (2024). Building on these foundations, the model is extended by introducing an explicit revenue formulation that links passenger demand, ticket pricing, and operational costs at the route level, an aspect that is largely treated separately in the existing literature.

The resulting model is solved using several conflicting objective functions, namely the minimization of total travel time, the minimization of total operated distance, and the maximization of revenue generated per route. These objectives are evaluated both individually and in a multi-objective setting. The formulation is subject to constraints on section capacity, terminal capacity, existing high-speed infrastructure, start and end times, and service frequency. By integrating and extending established line planning approaches within a unified framework tailored to Central European long-distance rail operations, the model enables the analysis of trade-offs that have not been adequately addressed in prior studies for this specific context.

With the examined Literature and defined problem in the scoped scenario several research questions can be formulated. With those the target of this paper is set, aiming to provide a satisfactory and meaningful answer to each of them. The following 4 questions are:

1. What is the optimal train line or combination of train lines in Central Europe on existing rail infrastructure, considering different train formations, operational constraints, and demand scenarios?
2. How do existing infrastructure limitations (e.g., existing network, passenger spread, capacity constraints) affect the feasibility and performance of different train line configurations on the Central European Network?
3. Which mathematical models from existing literature (e.g., nonlinear, mixed-integer, or bi-level models) are most suitable for adapting to the Central European high-speed rail context, and how can they be customized for this specific corridor?
4. What insights can be derived from applying the selected model to a European corridor that might inform future strategic planning by Deutsche Bahn (DB) and Österreichische Bundesbahnen (ÖBB)?

The final stage of the study situates the obtained results within the broader scholarly context by comparing the findings with those reported in the existing literature, identifying points of convergence as well as contrasting methodological or operational approaches. This discussion also

clarifies how specific concepts, modeling techniques, and analytical practices drawn from prior research were combined and adapted to construct the line planning model developed in this thesis.

3. Line Planning Problem

The line planning problem (LPP) constitutes a core strategic decision task in passenger railway planning, as it determines which train lines are operated on a given network, including their routes, stopping patterns, and service frequencies. These decisions directly shape the accessibility, efficiency, and economic performance of the rail system, while simultaneously constraining downstream planning stages such as timetabling, rolling-stock assignment, and crew scheduling. In high-speed and long-distance railway networks, line planning is particularly complex due to heterogeneous passenger demand, limited infrastructure capacity, and the need to balance conflicting objectives such as travel time minimization, cost efficiency, and passenger coverage. Especially in the European context, where high-speed, regional, and freight services share infrastructure, line planning must account for structural network constraints and operational feasibility from an early planning stage. Consequently, the LPP is commonly formulated as a mathematical optimization problem that selects an optimal subset of candidate lines from a predefined pool, subject to demand satisfaction, capacity limitations, and operational constraints, thereby providing a decision-support foundation for strategic railway service design.

3.1 Problem Definition

The high-speed railway system in Central Europe constitutes one of the most extensive and strategically significant rail infrastructures worldwide. Over the past decades, major investments have been made to improve cross-border connectivity, reduce travel times between metropolitan regions, and strengthen the competitiveness of rail against air and road transport. The result is a heterogeneous but dense network of newly built high-speed corridors and upgraded conventional lines that together form the backbone of passenger rail mobility in the region.

Central Europe is characterized by its polycentric structure, with numerous large metropolitan areas such as Paris, Berlin, Vienna, Hamburg, Warszawa, Budapest, Munich, Milano, Praha, Brussels, and Cologne lying within relatively short distances of each other. This urban constellation generates high demand for efficient long-distance transport, making rail particularly well-suited as a sustainable alternative to air travel. Modern trainsets such as the ICE, TGV, Railjet, Thalys, and ETR can reach operational speeds of 230–320 km/h, enabling competitive travel times on many international relations (European Union Agency for Railways, 2022).

Despite these technological capabilities, the current network is highly uneven. Certain corridors - such as Paris–Lyon, Frankfurt–Cologne, or Vienna–Budapest - allow sustained high-speed operation, while other stretches remain constrained by infrastructure limitations, bottlenecks in urban areas, or differing national standards. This results in fragmented travel times, where long-distance services alternate between very high-speed and significantly slower sections. As a consequence, the efficiency of the system is determined less by maximum train speed than by infrastructure continuity and network integration (Blomberg et al., 2025).

Overall, the Central European high-speed rail network combines impressive achievements in cross-border integration with persistent challenges of heterogeneity and coordination. For transport planners, this raises fundamental questions about how to design efficient line concepts that leverage high-performance infrastructure while accommodating uneven network conditions and diverse national priorities.

3.2 Current Situation

To narrow this broad theoretical framework to a concrete empirical application, it is essential to first examine the individual national railway networks within Central Europe. This step delineates the spatial and operational scope of the study by identifying the most relevant corridors and city nodes for inclusion in the model. Through a comparative analysis of existing high-speed and intercity infrastructures in each country, the research establishes a coherent and representative network foundation upon which the subsequent optimization and simulation processes are built. In doing so, the thesis ensures that the modeled system reflects both the geographical realities and the functional interconnections of the Central European rail landscape.

In the context of Central European rail planning, the key difficulty lies not only in the vast spatial coverage of the network but in the uneven operational environment through which services must run. Certain routes permit high-speed operation and modern service standards, whereas others remain limited by infrastructure age, technical constraints, or capacity shortages. This variability directly impacts travel times and complicates efforts to create coherent and efficient service patterns. Accordingly, planners must carefully calibrate train frequencies, stopping sequences, and vehicle allocations to align passenger demand with the realistic performance of the infrastructure.

Thus, the line planning task in Central Europe is less about pushing the limits of speed on individual corridors and more about optimizing coordination within a complex transnational system. Effective integration of major metropolitan centers - while ensuring that smaller cities remain accessible - depends on a balanced interaction between network capacity, demand distribution, and physical constraints. It is this balance that ultimately defines the functionality and attractiveness of the Central European rail system as a unified whole.

3.2.1 Germany

The Figure 1 on the right presents the German high-speed rail infrastructure, highlighting the distribution of newly built and upgraded corridors. Different colors indicate varying categories of high-speed lines: newly constructed tracks designed for velocities above 250 km/h (red), upgraded conventional lines permitting speeds up to 200–230 km/h (yellow), and further high-performance routes forming part of the long-distance network (blue). These corridors form a structural backbone for long-distance passenger transport, with major north–south and east–west axes linking metropolitan areas such as Hamburg, Berlin, Cologne, Frankfurt am Main, Stuttgart, Nuremberg, and Munich (Wikipedia, 2025a).

The strategic importance of Germany's high-speed network lies not only in its national connectivity but also in its position at the center of Central Europe. Germany acts as a transit hub that links the Western European networks of France, Belgium, and the Netherlands with the Eastern and Southeastern systems of Poland, Austria, Czechia, and beyond.

As such, the German infrastructure serves as a pivotal bridge in the trans-European transport system, enabling cross-border mobility on a continental scale (European Court of Auditors, 2018).

From a line planning perspective, these corridors represent both opportunities and challenges. On the one hand, they allow for the design of fast and competitive long-distance services between Europe's largest metropolitan areas. On the other hand, the alternation between newly built high-speed segments and conventional sections creates heterogeneity that complicates the formulation of coherent line structures. Consequently, effective line planning in Germany requires balancing the dual role of the network: providing efficient national connections while simultaneously ensuring international interoperability.

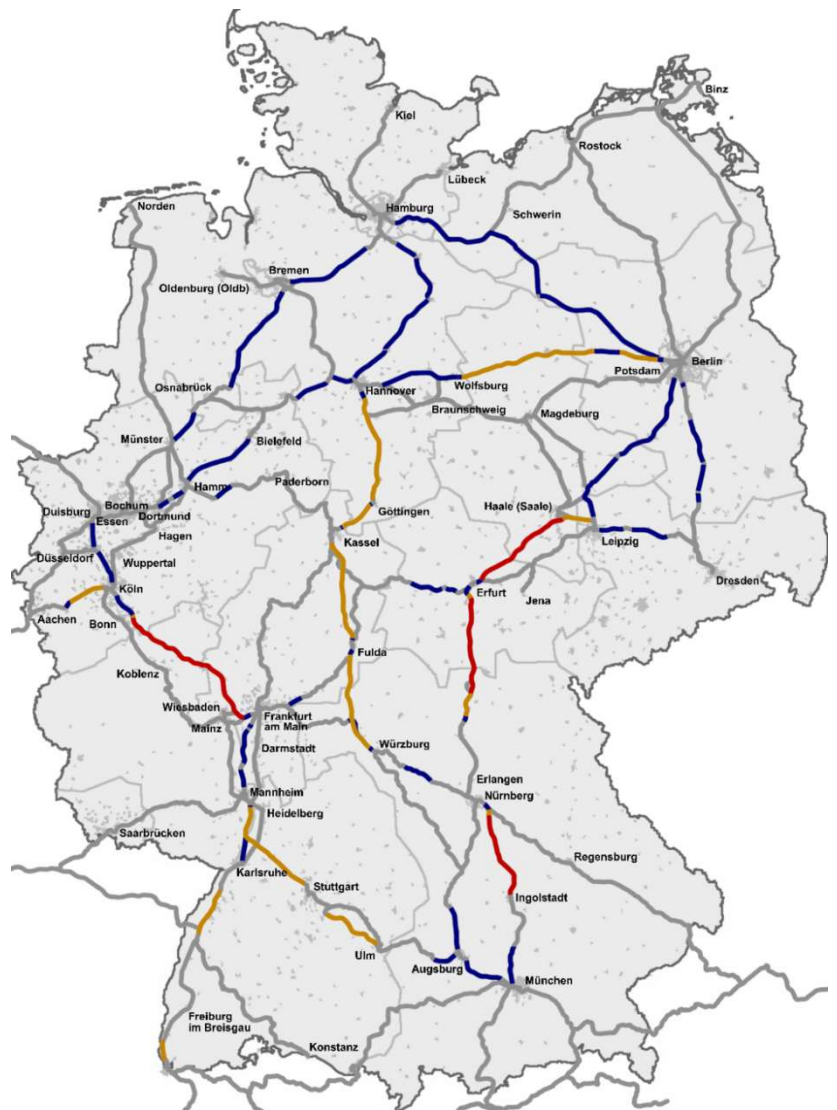


Figure 1: German highspeed railway network (Wikipedia, 2025a)

3.2.2 Austria

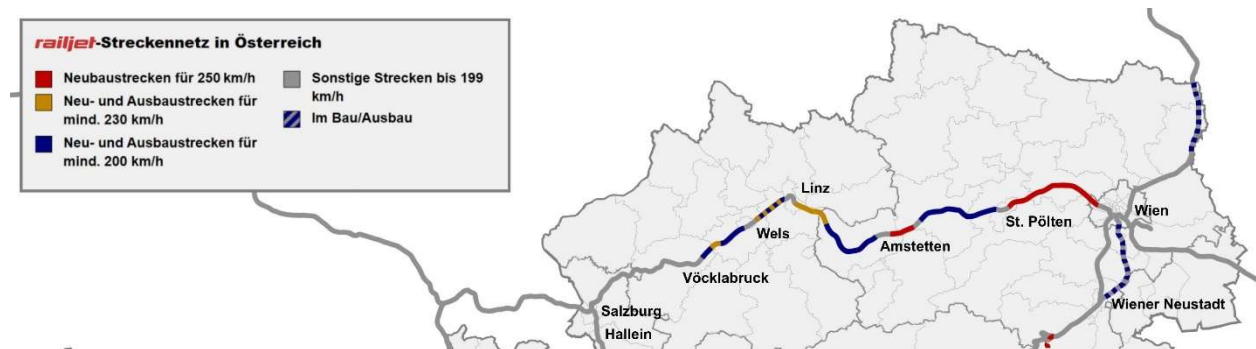


Figure 2: Austrian high-speed railway network (Wikipedia, 2025a)

Figure 2 illustrates the Railjet high-speed network in Austria, distinguishing individual track segments by design speed and infrastructure status. The legend differentiates five categories: newly built lines designed for 250 km/h (red), upgraded lines permitting 230 km/h (yellow), upgraded segments for 200 km/h (blue), conventional lines with lower speed limits (gray), and sections currently under construction or expansion (striped blue) (Wikipedia, 2025a).

The visualization clearly shows that Austria's principal high-speed axis extends from Vienna to Salzburg, passing through St. Pölten, Amstetten, Linz, Wels, and Vöcklabruck. The St. Pölten–Vienna stretch appears in red, indicating newly constructed infrastructure capable of the country's maximum operating speed of 250 km/h. West of this section, the Amstetten–Linz corridor (blue) supports speeds above 200 km/h, while the Linz–Wels–Salzburg area (yellow) features partially upgraded lines allowing up to 230 km/h. In contrast, gray-marked segments denote conventional track that still constrains performance, creating potential bottlenecks within an otherwise modernized corridor.

Overall, the figure underscores Austria's gradual and hierarchical approach to high-speed rail modernization, combining targeted new construction with systematic upgrades along key east–west transit axes. The Vienna–Linz corridor in particular exemplifies sustained infrastructure investment aimed at improving national and trans-European connectivity, thereby enhancing travel efficiency and integration within the broader TEN-T framework.

3.2.3 Italy



Figure 3: Italian high-speed railway network (Wikipedia, 2025a)

The provided Figure 3 highlights the structure of Italy's high-speed railway system, of which the northern section up to Bologna represents the most developed and operationally significant part. This area is defined by a continuous high-speed backbone running from Torino through Milano and Bologna to Fi-

renze, supported by ongoing extensions toward Venezia and Genova. With these connections, northern Italy concentrates the majority of the country's high-speed capacity and integrates several of its largest metropolitan areas within a compact corridor (Wikipedia, 2025a).

What makes this section particularly relevant is its dual function: it serves dense domestic travel demand while simultaneously acting as Italy's main gateway to the Central European rail network. Milano, in particular, emerges as the pivotal hub, linking transversal corridors and providing access toward France, Switzerland, Austria, and Slovenia. The short distances between major cities in this part of the network amplify the importance of careful line planning, as small adjustments in frequency, stopping patterns, or service combinations can significantly affect both capacity use and passenger distribution (INTERCONNECT, 2010).

In sum, the northern Italian high-speed system combines high density of demand, strong international connections, and ongoing infrastructure expansion. This creates both opportunities for efficient, high-frequency services and challenges in coordinating line structures within a network that must balance national priorities with European integration.

3.2.4 France

In the eastern half of France, the high-speed rail system radiates outward from Paris and demonstrates a strong corridor-based structure (Figure 4). The main axes extend toward Strasbourg, Lyon, and Lille, with further international continuations into Germany, Switzerland, Belgium, and Italy. These corridors illustrate a clear hierarchy: the Paris–Lyon line functions as the primary domestic spine, while the Paris–Strasbourg and Paris–Lille connections double as both national routes and international gateways. Particularly along the Paris–Strasbourg–Stuttgart/Frankfurt and Paris–Lille–Bruxelles axes, the infrastructure enables seamless integration into the Central European network (Wikipedia, 2025a).

What stands out in this region is the degree to which French high-speed infrastructure is embedded in cross-border mobility. Eastern France serves less as an isolated national system and more as a connector, ensuring that flows between Western and Central Europe can operate competitively. The positioning of Strasbourg and Lyon as nodal points underscores the dual function of this network segment: accommodating domestic flows while simultaneously facilitating international travel. For line planning, this creates a multi-scalar challenge, where services must align Paris-centered demand with Europe-wide connectivity (Crozet, Y., 2014).



Figure 4: France highspeed railway network (Wikipedia, 2025a)

3.2.5 Belgium

The Belgian high-speed rail system is structured around four dedicated lines (L.1–L.4), creating a compact but strategically significant network (Figure 5). The central hub is Bruxelles-Midi, from which lines radiate toward France (L.1), Germany (L.3), the Netherlands (L.4), and Liège (L.2). This radial configuration underscores Belgium’s dual role: while geographically small, it acts as a transit country within the broader European high-speed system, positioned at the intersection of north–south and east–west corridors.

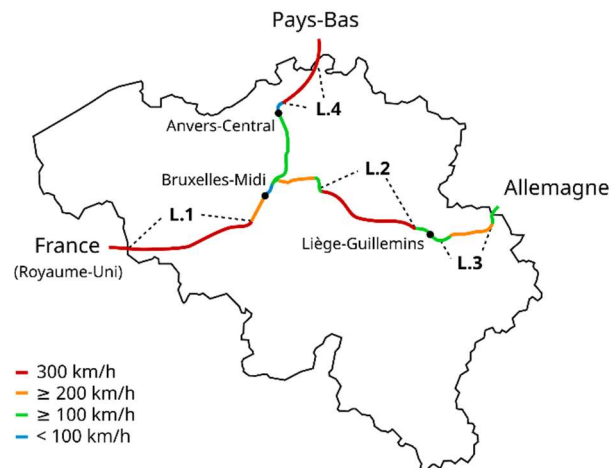


Figure 5: Belgium highspeed railway network (Wikipedia, 2025a)

The map illustrates how the infrastructure is functionally divided. L.1 and L.2 form the west–east axis, connecting Bruxelles with Paris and onward to Liège and Germany. L.3 strengthens the eastern link toward Aachen and Cologne, while L.4 establishes direct high-speed access between Bruxelles and Antwerpen, extending further into the Dutch network. The relatively short length of these lines compared to neighboring countries emphasizes that Belgium’s importance does not lie in domestic distances, but in providing seamless connections between major international hubs (Wikipedia, 2025a).

From a line-planning standpoint, the Belgian rail network exemplifies the complexity of coordinating a compact, radially oriented system with international service schedules. Because many key routes converge in Brussels and Liège, operational and scheduling choices within Belgium exert a direct influence on cross-border connectivity across both Western and Central Europe. Consequently, Belgium’s high-speed infrastructure should be viewed not as an isolated national framework, but rather as a strategic junction within the broader European rail architecture.

3.2.6 Netherlands

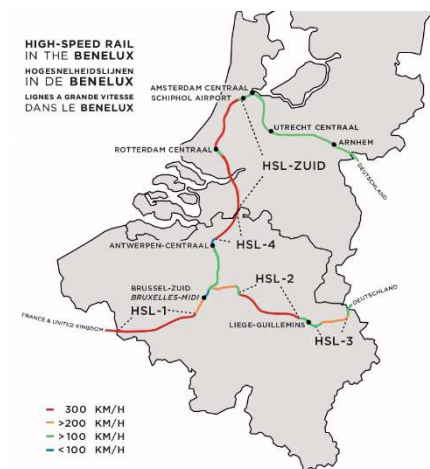


Figure 6: Netherlands highspeed railway network (Wikipedia, 2025a)

The Netherlands region has developed a compact but highly international high-speed rail system, consisting of four main corridors (HSL-Zuid, HSL-2, HSL-3, and HSL-4) (Figure 6). These lines provide direct connections between the major urban centers of the Netherlands and Belgium, while simultaneously linking them to the wider European network toward France, Germany, and the United Kingdom. Unlike larger countries where high-speed lines are primarily designed to reduce internal travel times, the Benelux network is shaped by its transit function. Paris, London, Frankfurt, and Cologne are all within reach through these corridors, underscoring the strategic role of this region as a gateway between northwestern and central Europe (Wikipedia, 2025a).

The infrastructure is not uniform in its standards: while several stretches, such as HSL-Zuid between Amsterdam, Rotterdam, and the Belgian border, allow operations up to 300 km/h, other segments operate at lower speeds. This mixture reflects both geographical constraints and the incremental approach taken in building the network. The presence of multiple cross-border routes also requires careful synchronization of timetables and rolling

stock, since trains must be compatible with different national systems within a relatively short distance (Global Railway Review, 2008).

For line planning, this setting introduces a particular complexity: the dense distribution of large cities in close proximity makes it necessary to balance express services between international hubs with frequent connections serving intermediate stops. Consequently, the Benelux high-speed network illustrates the challenges of designing a system that is at once locally accessible and internationally competitive.

3.2.7 Switzerland

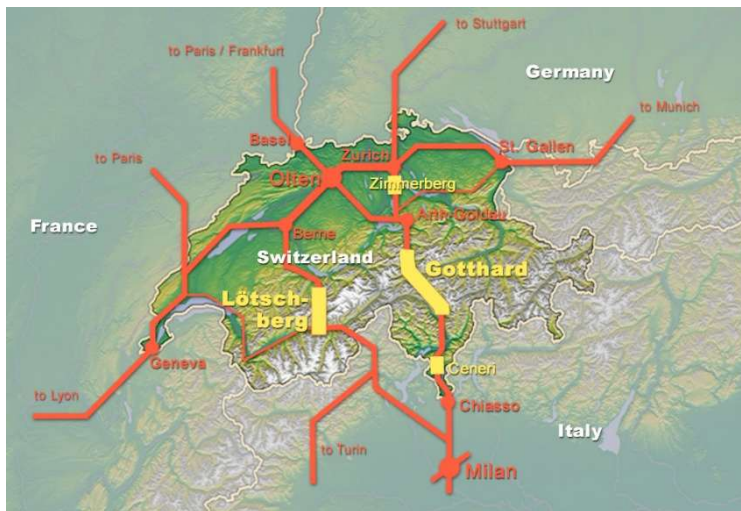


Figure 7: Swiss highspeed railway network (Wikipedia, 2025a)

Switzerland's rail network, as shown in the figure, plays a pivotal bridging role between northern and southern Europe (Figure 7). Unlike other countries where high-speed rail is designed primarily for domestic connections, the Swiss system is dominated by its function as a transit corridor across the Alps. The Gotthard and Lötschberg base tunnels, highlighted in yellow, are the most significant infrastructural elements: they provide low-gradient, high-capacity links that allow both passenger and freight trains to cross the Alpine barrier efficiently.

These corridors connect the northern gateways of Basel, Zürich, and Olten with Milan in the south, ensuring seamless continuity with the Italian high-speed system (Wikipedia, 2025a).

The overall structure of the Swiss network is highly nodal, with Zürich, Basel, and Olten emerging as central junctions. From here, the network branches out toward Germany (Stuttgart and Munich), France (Paris and Lyon), and Italy (Milan and Turin). Geneva and Bern further strengthen the western axis, tying the Swiss system into the broader Central European grid. Importantly, Switzerland's geography has shaped the network in such a way that international routes converge on a few alpine crossings, making the tunnels decisive bottlenecks as well as enablers of European north–south mobility (Schweizerische Eidgenossenschaft, 2025).

From a line-planning perspective, Switzerland constitutes a distinct case within Central Europe. Although the domestic distances between major cities are comparatively short, the network must simultaneously handle substantial international through-traffic. As a result, the Swiss rail system operates as a multilayered structure, where regional, intercity, and transnational services share and compete for the same infrastructure. This configuration demands high levels of operational coordination to ensure efficient use of limited network capacity. Consequently, Switzerland's high-speed and transit corridors are defined less by absolute velocity and more by their role in seamlessly integrating local accessibility with Europe's principal transport corridors.

3.2.8 Czech Republic

The map (Figure 8) depicts the current and planned structure of the Czech high-speed rail system in its Central European context. Unlike countries with already established high-speed corridors, Czechia is still in the preparatory phase of developing its network, as indicated by the dashed light blue lines. These projects are designed to link Prague with major domestic centers such as Brno, Ostrava, Plzeň, and Hradec Králové, while also creating strong cross-border connections toward Germany, Austria, Slovakia, and Poland. In parallel, the figure shows how the Czech plans are embedded into existing international high-speed infrastructure (dark blue), ensuring future interoperability with the broader European network (Wikipedia, 2025a).

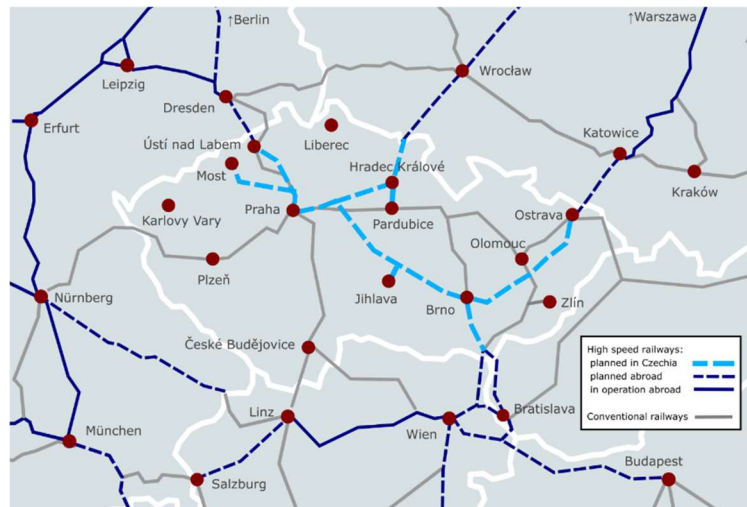


Figure 8: Czech highspeed railway network (Wikipedia, 2025a)

Geographically, Prague lies at the core of this planned system, functioning as the central hub from which corridors radiate outward. This radial structure mirrors the historical pattern of the Czech conventional rail system, but with a shift toward higher capacity and speed, aligning it with European standards. The strategic orientation of the network is evident in the planned links toward Nuremberg and Munich in the west, Vienna and Bratislava in the south, and Katowice and Kraków in the east. These routes emphasize the Czech Republic's role as a connector between Western and Eastern Europe (Svobada et al., n.d.a.).

From the perspective of rail network design, the Czech case exemplifies the challenge of reconciling domestic service provision with international transit objectives. The short spatial separations between major cities allow for dense service patterns and frequent departures, yet the cross-border orientation of the network requires careful synchronization with neighboring railway systems. Consequently, the development of a high-speed framework in Czechia reflects not only a technical modernization effort, but also an attempt to integrate a new layer of high-performance infrastructure into Europe's already complex and interdependent rail environment.

3.2.9 Poland



Figure 9: Polish highspeed railway network (Wikipedia, 2025a)

Poland's rail infrastructure, as shown in the figure, is still dominated by conventional lines with only limited segments upgraded to higher speeds (Figure 9). Existing corridors, particularly the central axis linking Warszawa, Gdansk, and Katowice, currently support maximum operating speeds of 200–230 km/h on selected stretches. These incremental upgrades place Poland below the Western European standard of purpose-built high-speed lines exceeding 300 km/h. Nevertheless, they represent important first steps in modernizing the network and ensuring compatibility with European high-speed operations (Wikipedia, 2025a).

Geographically, Poland's strategic role lies in its size and its function as a bridge between Central and Eastern Europe. Major nodes such as Warszawa, Kraków, Katowice, Wrocław, and Gdańsk anchor both domestic mobility and international flows toward Germany, Czechia, and the Baltic States. However, the lack of continuous high-speed corridors reduces overall competitiveness in travel times, particularly on cross-border routes. Planned projects, including the Centralny Port Komunikacyjny (CPK) rail program, aim to address this by creating a radial high-speed system centered on Warszawa, with new lines designed for up to 250–320 km/h operations (railway supply, 2024).

From the standpoint of rail line design, Poland embodies the complex task of simultaneously modernizing its conventional network and establishing a foundation for future high-speed operations. Given the country's large territorial scale, rail planning must reconcile long-distance domestic connectivity with the need for seamless integration into international corridors. In this context, Poland serves as a strategic laboratory for the eastward expansion of Central Europe's high-speed rail system, where national modernization aligns with broader trans-European ambitions.

3.2.10 Hungary & Slovakia

In the context of Central Europe, Budapest and Bratislava represent two strategically important nodes at the southeastern edge of the high-speed rail network. While both cities are currently served mainly by conventional rail infrastructure, planned projects aim to strengthen their integration into the European high-speed system. Bratislava functions as a natural extension of the Austrian network, with close proximity to Vienna making it a potential cross-border commuter and transit hub. Budapest, as the largest metropolitan area in the region, anchors long-distance flows toward the Balkans while also serving as a gateway between Central and Southeastern Europe. For line planning, the challenge lies in ensuring efficient connectivity between these two capitals and in linking them seamlessly with high-capacity corridors leading northward to Poland and westward through Austria into Germany (RAILWAYPRO, 2022; RAILTECH.com, 2025).

3.2.11 Slovenia & Croatia

Within the Central European rail network, Ljubljana and Zagreb form important southern nodes that connect the region to the Western Balkans. At present, both cities are primarily linked by conventional rail infrastructure, with limited high-speed capacity, yet they occupy a strategic position on the corridor running from Vienna through Ljubljana to Zagreb and further south. Their inclusion in the network highlights the role of this axis as a bridge between Central and South-eastern Europe. From a line planning perspective, services connecting Ljubljana and Zagreb must balance regional accessibility with the need to provide efficient long-distance connections toward major hubs such as Vienna, ensuring that the southern periphery is effectively integrated into the broader European system (Mobility Consultants, 2023).

4. Mathematical Formulation of LPP

Building on the comparative insights derived from the theoretical background and the review of existing railway systems across multiple countries, the methodology section now shifts from analyzing established networks to constructing the analytical framework required for this study. While previous sections emphasized structural characteristics, operational principles, and planning practices observed in real-world railway systems, the following methodological approach introduces a purpose-designed network tailored to the specific requirements of the line planning problem. This synthetic network serves as a controlled environment in which the interplay between infrastructure, demand patterns, and service design can be examined systematically. By defining the network's topology, operational constraints, and assumed demand flows, the study establishes a consistent basis for evaluating line plan configurations and exploring their implications for efficiency, connectivity, and resource utilization.

The line planning methodology is developed through a structured modeling sequence. It begins with the formal definition of the parameters that represent the key elements of the service environment, specifically time, distance, ticket prices, and the spatial distribution of passengers across the network. On this basis, the model specifies the objective function together with the decision variables defined over sets and parameters that encode these operational and demand-related characteristics. The formulation then introduces a system of constraints designed to ensure feasibility, respect network capacities, and reflect the fundamental requirements of the planning process. This stepwise construction of variables, objectives, and constraints provides a coherent foundation for the computational evaluation undertaken in the line planning analysis.

Define Sets

In the first step of formulating the line planning model, the relevant sets are defined to provide a structured representation of the railway network. Sets allow the model to clearly distinguish between different entities in the system and serve as the foundation for formulating both objective functions and constraints. In this case, the network can be described as a graph consisting of nodes and arcs. The set of nodes is defined as

$$N = \{1, 2, \dots, 117\},$$

where each element corresponds to a railway station, ranging from Turin (1) in the east to Paris (12) in the west, and including intermediate stops in Austria, Germany, Switzerland, Poland, Belgium, Netherlands, Slovakia, Croatia and the Czech Republic. The set of arcs is defined as

$$A \subseteq N \times N,$$

which represents all feasible and valid connections between two stations, where an arc $(i, j) \in A$ exists if there is a direct connection from node i to node j . For example, the Route from Turin to Venice is represented by arcs such as

$$A_{main} = \{(1,2), (2,3), (3,5), (5,4)\},$$

Additional cross-links, for instance between Ingolstadt (74) and surrounding cities, are summarized in a set $A_{feasible}$. By structuring the problem in terms of such sets, the model gains clarity and flexibility: it becomes straightforward to define which links are admissible, to track alternative routing options, and to ensure consistency across the various data matrices (distance, time, cost, and passenger distribution). This formalization of sets is therefore crucial to translate the conceptual railway corridor into a mathematical framework that can be optimized.

4.1 Parameter Generation

Defining the parameters for the line planning problem is a crucial step, as they form the quantitative foundation upon which all subsequent modeling and optimization rely. Accurate parameter definitions ensure that the mathematical representation of the network reflects both its physical constraints and operational realities. However, the process is subject to several inherent limitations. One important constraint arises from the structure of feasible solutions: within the optimization framework, a line cannot form a looped route, as circular services would not represent operationally meaningful or economically efficient solutions. Instead, every route must have a clearly defined origin and destination, ensuring directional flow and avoiding redundant network circulation.

Another limitation lies in the estimation of travel costs, since railway pricing policies differ among operators and are often non-transparent, making precise fare estimation challenging. To mitigate this, average observed ticket prices have been used as a practical approximation for revenue modeling. Furthermore, detailed passenger flow data at the station level is not publicly available, requiring the adoption of a Markov chain-based approach to estimate passenger distribution and interchange probabilities within the network. Similarly, the cost side of the model relies on assumptions derived from existing literature (Meng, 2020; Chen et al., 2024), including approximations of track access charges, maintenance expenses, and personnel costs. These literature-based estimates provide a consistent but simplified representation of real operational conditions, ensuring comparability across routes while acknowledging the inherent uncertainty in cost modeling.

These constraints must be carefully considered when interpreting the model results, as they define the operational boundaries within which the line planning problem can be meaningfully analyzed and optimized.

Number	Name	Population	Country	lon	lat	Tier	Share Pop	Cum Share Pop
1	Turin	841.600	IT	7.69	45.07	B	1,650%	44,322%
2	Genua	558.745	IT	8.95	44.41	C	1,095%	59,776%

3	Milan	1.371.498	IT	9.19	45.46	A	2,689%	31,959%
4	Venice	250.369	IT	12.32	45.44	F	0,491%	83,208%
5	Bologna	390.734	IT	11.34	44.49	E	0,766%	70,315%
6	Triest	200.562	IT	13.78	45.65	F	0,393%	88,885%
7	Nizza	345.548	FR	7.27	43.71	E	0,677%	73,903%
8	Udine	98.243	IT	13.23	46.07	G	0,193%	98,453%
9	Bozen	107.227	IT	11.35	46.50	G	0,210%	97,657%
10	Marseille	873.076	FR	5.37	43.30	B	1,711%	42,672%

Table 1: List of cities with their specific Information

The table 1 excerpt presents a subset of the 117 cities included in the Central European network model used for the line planning problem. Each entry lists the city's unique identifier, name, population, data source, country, geographical coordinates (longitude and latitude), and its assigned tier classification, which reflects the city's relative importance within the network. The population share and cumulative population share quantify each city's demographic contribution to the overall system and serve as weighting factors in demand estimation and service allocation within the model.

This particular segment includes ten cities, primarily located in northern Italy and along the southern Alpine corridor, complemented by two French cities - Nice and Marseille. The population figures range from 98,243 (Udine) to 1,371,498 (Milan), illustrating the substantial variation in urban scale within this regional cluster. Milan clearly emerges as a Tier A city, representing a major metropolitan and economic hub, while smaller cities such as Udine and Bolzano fall into Tier G, corresponding to regional or peripheral centers. Mid-sized cities like Turin, Marseille, and Genoa occupy Tier B and C categories, reflecting their intermediate but strategically relevant positions within the network hierarchy. This tier allocation, further detailed in the section on passenger spread computation, forms a crucial input for estimating passenger demand, as it defines the relative weighting of origin and destination nodes within the modeled network. The population shares highlight Milan's demographic dominance, accounting for approximately 2.7% of the total modeled population, followed by Marseille (1.7%) and Turin (1.6%). The cumulative population shares indicate that a small number of large cities contribute disproportionately to the overall network demand, a pattern consistent with real-world urban hierarchies and mobility structures.

Crucially, this dataset constitutes a fundamental prerequisite for solving the line planning problem, as it defines the underlying spatial and demographic framework on which the optimization model operates. The city population, location, and tier classification jointly determine both the potential passenger demand and the relative connectivity of each node in the network. Without such detailed and structured input data, it would not be possible to generate meaningful or realistic optimization results for the Central European railway system.

4.2 Railway Network Definition

Before moving on to the key Mathematical Formulation, it is necessary to outline the current state of the Central European rail network. The system comprises 117 cities and extends across multiple countries, connecting major metropolitan areas such as Berlin, Paris, Vienna, Hamburg, Warszawa, Budapest, Munich, Milan, Praha, Brüssel, and Cologne. This dense web of connections forms one of the most important transport backbones in Europe, combining high-speed, intercity, and regional services within a single integrated network. The selection of cities was derived from the previously introduced national railway network maps of the respective Central European countries, complemented by manually identified high-speed corridors based on the currently operating train services in each country. This combined data approach ensures that the resulting network not only reflects the geographical and infrastructural realities of the Central European rail system but also captures its functional relevance in terms of existing service patterns and cross-border connectivity.



Figure 10: Railway network for the model

The self-created Figure 10 illustrates the spatial structure of the Central European railway network, modeled as a graph consisting of nodes and edges. Each node represents an urban center with rail access, while edges denote direct railway connections between these cities. The network covers a broad geographic area, stretching from northern Germany to southern Italy and from eastern Poland to southern France. Prominent metropolitan areas such as Paris, Berlin, Vienna, Milano, and Warszawa function as highly connected hubs within the system, while smaller cities are integrated through fewer but strategically relevant links. The overall topology displays a combination of dense regional clusters - particularly visible in western Germany, the Benelux area, and northern Italy - and long-distance international connections bridging these clusters across national borders. Such a structure reflects both historical development patterns and current demand for cross-border mobility. From a line planning perspective, this spatial configuration presents challenges in balancing hub-to-hub express services with coverage of peripheral nodes, as

the dense central corridors compete with more sparsely connected regions for capacity. The figure thus provides the foundation for analyzing how line planning strategies can optimize connectivity, frequency, and travel times in a network characterized by both regional density and international span.

To enable spatial modeling within the Central European rail network, geographical coordinates (longitude and latitude) were first collected for all 117 cities using data from latlon.net (latlon.net, 2025). These coordinates provide the spatial foundation for subsequent distance and network analyses. Using various Python libraries, including GeoPandas, Matplotlib.pyplot, Pandas, and Shapely.geometry, the geographical data were processed and visualized. The implemented script automatically positioned each city at its correct geographic location on the map based on its coordinates, resulting in an initial plot showing all nodes accurately distributed across Central Europe.

Number	Name	Population	Source	Country	lon	lat
1	Turin	841.600	Link zum ISTAT (Ital. Statistikamt)	IT	7.69	45.07
2	Genua	558.745	Link zum ISTAT (Ital. Statistikamt)	IT	8.95	44.41
3	Mailand	1.371.498	Link zum ISTAT (Ital. Statistikamt)	IT	9.19	45.46
4	Venedig	250.369	Link zum ISTAT (Ital. Statistikamt)	IT	12.32	45.44
5	Bologna	390.734	Link zur Metropolitanstadt Bologna (Wikipedia)	IT	11.34	44.49
6	Triest	200.562	Link zum ISTAT (Ital. Statistikamt)	IT	13.78	45.65
7	Nizza	345.548	Link zum INSEE (Franz. Statistikamt)	FR	7.27	43.71
8	Udine	98.243	Link zum ISTAT (Ital. Statistikamt)	IT	13.23	46.07
9	Bozen	107.227	Link zur Statistik Provinz Bozen	IT	11.35	46.50
10	Marseille	873.076	Link zum INSEE (Franz. Statistikamt)	FR	5.37	43.30

Table 2: Information table for each city

For the cartographic base, country boundaries were retrieved from the publicly available Natural Earth dataset (50 m scale) (Table 2). The corresponding shapefile was accessed directly via its cloud repository and imported into a GeoDataFrame. A Shapely bounding box polygon was created to represent the Central European extent, and all country geometries intersecting with this area were extracted. This subset formed the spatial framework for visualization.

Origin	Connection 1	Connection 2	Connection 3	Connection 4	Connection 5	Connection 6
Turin	Genua	Mailand	Nizza	Valence		
Genua	Turin	Nizza	Mailand	Bologna		
Mailand	Turin	Genua	Bologna	Venedig	Bozen	Luzern
Venedig	Bologna	Mailand	Bozen	Udine		
Bologna	Genua	Mailand	Venedig			

Table 3: Connection table

At this stage, the visualization displayed only city locations, without inter-city connections. To represent the underlying rail network structure, a separate connections table (Table 3) was manually created, listing all plausible direct links between the cities. In total, 380 potential inter-city connections were identified, corresponding to all realistic direct rail links in the modeled network.

Citynumber	Origin	Citynumber2	Destination
1	Turin	2	Genova
1	Turin	3	Mailand
1	Turin	7	Nizza
1	Turin	20	Valence
2	Genova	1	Turin

Table 4: Connection edge list

To complement the manually constructed connection table (Table 4) and to derive empirically grounded rail distances, a dedicated route-generation procedure was implemented. This procedure is encapsulated in a Python script that programmatically interfaces with OpenStreetMap through the Overpass API. The approach builds on the city list defined in the parameter file and uses these coordinates to extract localized railway-network segments. For each city pair specified the script automatically formulates a spatial query to OpenStreetMap, requesting all relevant railway elements - main lines, branch lines, and lines without explicit usage tags - within a dynamically sized bounding box that reflects the approximate geographical distance between the two cities.

The script retrieves these data as JSON responses, which are subsequently transformed into GeoJSON files representing the raw railway geometry around each origin–destination pair. These files serve as cached network snippets, ensuring that identical queries are not sent repeatedly to the Overpass API and thereby reducing computational time during subsequent runs. Within each cached snippet, the code converts the railway geometries into a graph structure using NetworkX, where nodes correspond to coordinate points along the tracks and edges represent individual rail segments weighted by their metric length. The shortest-path computation is then performed between the nodes nearest to the two cities of interest, yielding an approximation of the shortest continuous rail route under the constraints of the extracted network.

If a valid path is identified, the resulting route is simplified, stored as a GeoJSON file in a structured cache system, and appended to the aggregate network representation. In parallel, a tabular record of the computed rail distances is written to an Excel file for subsequent analytical use. In instances where no feasible path exists within the initial bounding box, the script automatically expands the query buffer and retries the extraction up to predefined limits. Once all city pairs have been processed, the individually computed shortest-path segments are merged into a comprehensive geospatial dataset, representing the real-world rail network relevant to the study. This integrated network forms the empirical foundation upon which the subsequent methodological steps - network construction, line planning, and model validation - are based.

Using Matplotlib in conjunction with GeoPandas' plotting functions, a multi-layered visualization was created.

The following elements were drawn sequentially:

1. Country boundaries – black outlines to delineate the study region,
2. City points – red markers corresponding to node locations.
3. Connection routes – gray, semi-transparent lines representing intercity links,

City names were annotated according to the predefined label positions. Axes and coordinate grids were removed for aesthetic clarity, and the map extent was constrained to the Central European bounding box. The final figure titled “Central Europe – Railway Network” served as a visual representation of the modeled network.

4.2.1 Distance Matrix

Based on the generated GeoJSON files, an additional script was developed to compile the complete railway network into a GeoPackage (GPKG) format. This file structure enabled efficient spatial processing and visualization of the network, providing a practical foundation for subsequent analytical and cartographic operations. The resulting dataset served as the basis for the visual representation shown in *Figure 10*, illustrating the modeled rail connections across the study area. Furthermore, the previously computed distances was imported into Python to construct a 117×117 distance matrix, representing the shortest railway distance between every pair of cities within the network. To generate the 117×117 distance matrix, the network graph constructed from the calculated railway distances was analyzed using Dijkstra’s shortest-path algorithm. Each city served as a node and each intercity connection as an undirected edge weighted by its real-world distance. Through the networkx library’s all-pairs Dijkstra implementation, the minimum cumulative distance between every city pair was computed, yielding a symmetric and fully connected matrix. This approach ensures an exact and reproducible estimation of the shortest physical railway distances, forming a consistent input for subsequent demand and route optimization models. While the method accurately captures geometric shortest paths, it does not incorporate operational parameters such as travel times or scheduling constraints, which could affect real-world network performance. This matrix formed a key input for later stages of the modeling process, particularly for demand estimation and route optimization analyses.

		1	2	3	4	5
	Dij	Turin	Genua	Mailand	Venedig	Bologna
1	Turin	0,0	227,0	209,8	601,2	524,7
2	Genua	227,0	0,0	210,3	601,7	404,1
3	Mailand	209,8	210,3	0,0	391,4	314,9
4	Venedig	601,2	601,7	391,4	0,0	228,9
5	Bologna	524,7	404,1	314,9	228,9	0,0

Table 5: Snipped from the Distance Matix

For illustration, consider the subroute from Turin (1) to Venedig (5) following the sequence
1 → 2 → 3 → 5 → 4.
That means that we can now calculate the overall distance by summing the leg-distances from the distance matrix.

$$\begin{aligned}
D_{1,2,3,5,4} &= d_{12} + d_{23} + d_{35} + d_{54} \\
&= 227,0 + 210,3 + 314,9 + 228,9 = 981,1
\end{aligned}$$

4.2.2 Time Matrix

The second modeled parameter is the travel time between stations, which is minimized either directly (when journey-time is the primary objective) or used as a weighted component alongside

distance and cost. Travel times were extracted from the respective train operators' timetables for each direct connection individually and then aggregated into the time matrix in the same format as the distance data (ÖBB, 2025c; Belgiantrain, 2025; SBB, 2025; Ceske drahy, 2025; Deutsche Bahn, 2025d; SNCF Connect, 2025; HZPP, 2025; MAV-Group, 2025; italoireno, 2025; NS, 2025; PKP Intercity, 2025; Železničná spoločnosť Slovensko, 2025; Slovenske železnice, 2025). Time is an immediate performance indicator for passengers and a driver of operational choices (time-tabling, train-kilometre productivity, and required rolling-stock rotations).

For the alignment 1→2→3→5→4 (Turin → ... → Venedig), the objective aggregates admissible inter-station times from the time matrix (Table 6):

$$T_{1,2,3,5,4} = t_{1,2} + t_{2,3} + t_{3,5} + t_{5,4} \\ = 109 + 86 + 61 + 73 = 329$$

		1	2	3	4	5
	Tij	Turin	Genua	Mailand	Venedig	Bologna
1	Turin	0	109	45	179	106
2	Genua	109	0	86	219	146
3	Mailand	45	86	0	134	61
4	Venedig	179	219	134	0	73
5	Bologna	106	146	61	73	0

Table 6: Snipped from the Time Matix

This total travel-time of 329 minutes provides a direct passenger-centric benchmark for comparing alternative alignments and for multi-objective trade-offs against distance and cost.

4.2.3 Ticket Price Matrix

The third variable captures ticket prices, which are inherently more complex than distance or time because fares are not fully transparent and follow operator-specific revenue-management rules. To obtain comparable inputs, fares were empirically collected from the operators' booking sites for each admissible origin–destination pair, sampled every Saturday for two advance-purchase settings - next day and two months ahead - over the past two months (ÖBB, 2025c; Belgiantrain, 2025; SBB, 2025; Ceske drahy, 2025; Deutsche Bahn, 2025d; SNCF Connect, 2025; HZPP, 2025; MAV-Group, 2025; italoireno, 2025; NS, 2025; PKP Intercity, 2025; Železničná spoločnosť Slovensko, 2025; Slovenske železnice, 2025). All observations refer to one adult, 2nd class, without discounts. The average over these observations defines the entry of the ticket-price matrix (Table 7). Example for the reference journey 1→5, the total fare is the sum of intermediate segments:

		1	2	3	4	5
	Pij	Turin	Genua	Mailand	Venedig	Bologna
1	Turin	0	13,675	11,95	46,4	36,85
2	Genua	13,675	0	12,5	46,95	31,5
3	Mailand	11,95	12,5	0	34,45	24,9
4	Venedig	46,4	46,95	34,45	0	22,45
5	Bologna	36,85	31,5	24,9	22,45	0

Table 7: Snipped from the Ticket Price Matix

$$P_{1,2,3,5,4} = t_{1,2} + t_{2,3} + t_{3,5} + t_{5,4} \\ = 13,675 + 12,5 + 24,9 + 22,45 = 73,53$$

If a reverse-indexed but admissible pair appears (e.g., $5 \rightarrow 4$), the value is taken from the symmetric stored cell $p_{5,4}$. This formulation reflects both the empirical nature of fare data and the additive structure of rail pricing while providing a consistent, reproducible input for optimization.

4.2.4 Operating costs

While passenger demand and ticket prices determine the potential revenue generated by each modeled service, assessing overall economic performance also requires a realistic representation of the associated operational costs. These costs capture the financial effort required to operate a train along a given corridor and are essential for calculating operating profit and margin, which serve as the main indicators of route-level viability in the benchmark analysis. To ensure consistency with the revenue model, the cost structure was defined at a comparable level of granularity - on a per-kilometer, per-hour, and per-stop basis - allowing each service to be evaluated under uniform and transparent assumptions. The following section outlines the cost components and parameterization applied in the model, derived from recognized industry reports and academic sources to approximate realistic expenditure conditions across different European countries.

The operational cost model was constructed using literature-based parameters to represent realistic expenditure levels for long-distance passenger rail services in Central Europe. The track access charges (TAC) were primarily derived from the Wettbewerber-Report Eisenbahnen 2023/24 published by Die Güterbahnen, specifying a base value of 7.0€ per train-kilometer, with country-specific adjustments reflecting the diversity of European infrastructure charging schemes. In particular, the model applies 15.52€/km for Germany, 1.42€/km for Austria, 9.77€/km for France, 4.09€/km for Italy, 4.85€/km for Switzerland, and 1.24€/km for the Czech Republic (MOFAIR, 2023). Additional variable costs for energy consumption and maintenance were set to €2.3 per train-kilometer, following estimates provided by the Technische Universität Wien (TU Wien, Institute of Transportation). Personnel costs were modeled at €111 per train-hour, based on typical staffing levels and hourly wages for high-speed operations reported by the same source (Fally F., TU Wien, 2014).

To account for operational expenses incurred at stops, a station fee of €50 per scheduled stop (applied at terminal stations) (Signalarchiv, 2025). Furthermore, a border-crossing surcharge of €300 per crossing was introduced to represent the administrative, communication, and logistical efforts associated with international operations. A fixed cost component was set to zero in this version of the model, reflecting the focus on variable, distance-dependent, and operationally relevant expenses. Collectively, these parameters provided a transparent and harmonized framework for estimating route-level operating costs across the benchmark network, while allowing for sensitivity analyses based on national cost differentials.

In summary, the defined cost structure provides a consistent and transparent framework for quantifying the operational expenditures of each modeled connection. Building on this financial foundation, the subsequent section introduces the passenger spread model, which distributes overall demand across the network and forms the basis for estimating passenger flows and station-level boarding patterns.

4.2.5 Passenger Spread

The table 4 provides the population data that was used to construct the attractiveness component of the passenger spread model. Each city corresponds to one of the 117 stations included in the network, ranging from Berlin (3,782,716 inhabitants) as the largest urban center to Plattling

(13,121 inhabitants) as the smallest. Large metropolitan areas such as Vienna (2,005,101), Munich (1,510,378), and Prague (1,357,326) clearly dominate in terms of population size, whereas intermediate regional centers like Nuremberg (523,026), Linz (212,538), and Regensburg (158,423) represent important secondary hubs. Smaller towns such as Passau (54,123), Budweis (97,377), and Reims (181,194) were also included to reflect the full spatial connectivity of the network. The inclusion of all stations ensures that both major long-distance passenger flows and smaller regional connections are adequately represented. These population figures serve as the quantitative input for the attractiveness matrix, where they are logarithmically transformed and weighted to smooth out extreme values and prevent the dominance of very large cities such as Vienna or Munich. In doing so, the model balances the realistic tendency of passengers to travel towards larger metropolitan centers for work or tourism with the structural importance of smaller intermediate stations along the route. This was achieved by constructing a Gauß–Markov distribution as it was not possible to retrieve an official attractiveness ranking covering all cities. Attractiveness was proxied by city population, using the formula

$$a_{ij} = \frac{\ln (Pop_j + 1)^b}{\ln (Pop_i + 1)^a}$$

Where Pop_i is the population of the origin city i , and a and b are weighting factors. Those factors reflect the empirical fact that larger destinations (e.g., Vienna, Munich) naturally attract more passengers due to tourism, employment, or other opportunities. For that all cities above a population of 1 mio. received the Tier A (Table 8). Those cities are already responsible for 40% of the overall population across the whole network. From there on the Tiers B to G where given in 10% steps of the cumulative overall network population (Amsterdam → B, Leipzig → C, Plattling → G). The formula then retrieves the denoting values from a table according to the Tiers of the cities. The logarithmic transformation was introduced to smooth extreme outliers, ensuring that very large cities do not disproportionately dominate the distribution.

A	B	C	D	E	F	G
1,6	1,5	1,4	1,3	1,2	1,1	1

Table 8: Teir list with denoting value

From this attractiveness matrix, a probability matrix was generated, normalizing each row such that the sum equals 1, as required in a stochastic passenger distribution. This means, for example, that the row representing Vienna indicates the full spread of passenger flows to all feasible destinations. The final passenger spread matrix combines the three dimensions - attractiveness, travel time, and distance - into a weighted average, with weights $w_a = 1000$ for attractiveness, $w_t = 0.5$ for travel time, and $w_d = 0.8$ for distance:

$$Pas_{ij} = \frac{w_a * a_{ij} + w_t * T_{ij} + w_d * D_{ij}}{\sum_{k=1}^n (a_{ik} + T_{ik} + D_{ik})}$$

where T_{ij} denotes travel time and D_{ij} the travel distance. The denominator ensures normalization across all destinations k , maintaining the stochastic property. The outcome reflects the behavioral assumption that passengers prioritize city attractiveness (jobs, tourism) more than time or distance minimization when selecting destinations.

		1	2	3	4	5
Pij		Turin	Genua	Mailand	Venedig	Bologna
1	Turin	-	2	4	2	2
2	Genua	3	-	4	2	2
3	Mailand	2	2	-	1	1
4	Venedig	5	4	6	-	2
5	Bologna	4	3	5	1	-

Table 9: Snipped from absolute passenger spread matrix

Based on the final probability matrix, the passenger distribution along the investigated route can be derived under the assumption of a maximum train capacity of 372 passengers. The table 9 illustrates how the inflow and outflow of passengers develops along stations 1 to 5. The cells provide the exact number of passengers originating at a given station and their corresponding destinations. It is important to note that this distribution is calculated under the simplifying assumption that only a single train operates across the entire network. Consequently, the total of 372 passengers is distributed across all origin–destination relations of the network, allowing individual trains to potentially reach their maximum load but not exceeding it.

In the subsequent solver-based analysis, however, the network is operated by seven trains simultaneously, corresponding to the seven benchmark routes. This increases the theoretically available number of passengers at each station by a factor of seven, resulting in more realistic utilization levels for each train. At the same time, the benchmark route evaluation is intentionally conducted under the one-train assumption. This ensures a consistent and comparable basis across all routes, thereby isolating structural characteristics of each corridor without confounding effects from fleet scaling.

Nevertheless, care must be taken when interpreting profitability and capacity utilisation, as some routes do not approach capacity limits or fail to generate a profit under the single-train scenario. This is an expected outcome of the design choice: the one-train model allows direct comparison across benchmark routes, while real-world scenarios with larger fleets would simply scale demand and revenue proportionally - provided that capacity constraints remain satisfied.

4.3 Mathematical Formulation

To formally represent the line planning problem, this thesis adopts a mixed-integer linear programming (MILP) formulation. The MILP framework is particularly well suited to the line planning context, as it allows discrete strategic decisions - such as the selection of train lines and their operating frequencies - to be combined with continuous flow-based representations of passenger demand within a unified optimization model. Moreover, linear formulations ensure computational tractability for large-scale railway networks, enabling systematic evaluation of multiple candidate line configurations under realistic operational constraints.

In order to manage the inherent complexity of the problem and to maintain solvability at the network scale considered, several simplifying assumptions are introduced:

1. Direct travel assumption: All passengers are assumed to travel directly from their origin to their destination without transfers.

2. Unlimited willingness to pay and travel: Passenger choices are not constrained by budget or time limitations.
3. Demand–frequency proportionality: Passenger demand is assumed to scale proportionally with the number of operated train services.
4. Homogeneous rolling stock: Only a single train type is considered, and all trains are assumed to have identical seating capacity.

These assumptions allow the line planning problem to be expressed as a linear optimization model while preserving its essential structural characteristics. The resulting MILP formulation provides a transparent and computationally efficient foundation for analyzing trade-offs between service coverage, operational efficiency, and network performance within the Central European railway system.

Parameters:

A :	Set of train lines.
d_{ij} :	Distance between two cities i and j .
$\tilde{D}_{ij}$:	Normalized Time
t_{ij} :	Time between two cities i and j .
$\tilde{T}_{ij}$:	Normalized Time
p_{ij} :	Ticket price between two cities i and j .
K_{ij} :	Total Costs
$\widetilde{Prof}_{ij}$:	Normalized Profit
a_{ij} :	Attractiveness between cities i and j .
Pop_{ij} :	Population of Origin/Destination City.
w_a :	weighted distribution for attractiveness
w_t :	weighted distribution for time
w_d :	weighted distribution for distance
Pas_{ij} :	Passenger spread between cities i and j .
c_{ij} :	operating costs between cities i and j .
TAC_{ij} :	track access charge per train-kilometer [€/km]
VAR_{ij} :	variable cost per train-kilometer for energy and maintenance [€/km]
$STAFF_{ij}$:	staff cost per train-hour [€/h]
$STOP_{ij}$:	station fee applied at the terminal station [€]
$BORDER_{ij}$:	border-crossing surcharge applied if i and j lie in different countries [€]
FIX :	fixed cost per train run [€]
R :	Total revenue for train line.
C :	Total costs for train line.
Cap :	Seat capacity of one train

Decision variables:

Fleet size:	Amount of operating trains in the network
x_{ij} :	Binary variable, equal to 1 if line ij used, and 0 otherwise.
f_{ij} :	Frequency of the line i to j .

Objective Functions:

$$REV_r = \sum_{(i,j) \in A} x_{ij} \cdot p_{ij} \quad (1)$$

$$COST_r = \sum_{(i,j) \in A} x_{ij} \cdot K_{ij} \quad (2)$$

$$\min Z_{time} = \sum_{(i,j) \in A} t_{ij} \cdot x_{ij} \quad (3)$$

$$\min Z_{dist} = \sum_{(i,j) \in A} d_{ij} \cdot x_{ij} \quad (4)$$

$$\max \sum_{(i,j) \in A} (\text{REV}_r \cdot f_r - \text{COST}_r \cdot f_r), \quad (5)$$

$$\min w_t \sum_{(i,j) \in A} \tilde{T}_r x_r + w_d \sum_{r \in R} \tilde{D}_r x_r - w_{Prof} \sum_{r \in R} \widetilde{Prof}_r f_r \quad (6)$$

Constraints:

$$\sum_{j:(i,j) \in A} x_{ij} - \sum_{j:(j,i) \in A} x_{ji} = \begin{cases} 1 & \text{if } i = O \\ -1 & \text{if } i = D \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

$$\sum_{j:(O,j) \in A} x_{Oj} = 1, \quad \sum_{(i,D) \in A} x_{iD} = 1 \quad (8)$$

$$\sum_{(i,j) \in A} Pas_{ij} \cdot x_{ij} \leq Cap \quad (9)$$

$$\sum_{j:(i,j) \in A} Pas_{ij} = \text{boarding at } i, \quad (10)$$

$$\sum_{j:(j,i) \in A} Pas_{ji} = \text{alightings at } i, \quad (11)$$

$$x_{ij} \in \{0,1\} \quad \forall (i,j) \in A \quad (12)$$

$$y_{ij} \in \{0,1\} \quad \forall (i,j) \in A \quad (13)$$

$$f_{ij} \in \mathbb{Z}_{\geq 0} \quad \forall (i,j) \in A \quad (14)$$

$$\text{Fleet Size} \in \mathbb{Z}_{\geq 0} \quad (15)$$

Equations (1) and (2) define the revenue and cost components of an operated line, where total revenue is obtained by summing the ticket revenues p_{ij} over all activated arcs (i,j) , and total cost is computed analogously using arc-specific operating costs K_{ij} . Objectives (3) and (4) represent single-criterion formulations that minimize total travel time and total travel distance, respectively, by selecting arcs with minimal accumulated travel times t_{ij} or distances d_{ij} . Objective (5) formulates profit maximization by scaling route-specific revenues and costs with the corresponding service frequencies f_r , thereby capturing the effect of operating multiple train services on economic performance. Objective (6) extends these formulations to a normalized multi-objective setting, combining travel time, travel distance, and profit into a single weighted objective function; travel time and distance enter as minimization terms, while profit is incorporated with a negative sign to maintain a minimization structure, and the weights w_t , w_d , and w_{Prof} control the relative importance of each criterion. Constraint (7) enforces flow conservation to ensure a valid path from the origin node to the destination node, while constraint (8) guarantees the uniqueness of the selected route by requiring exactly one outgoing arc from the origin and one incoming arc to the destination. Constraint (9) imposes seat-capacity limits, ensuring that passenger volumes assigned to the selected arcs do not exceed the available train capacity. Constraints (10) and (11) define passenger boarding and alighting processes at each station as the sum of outgoing and incoming passenger flows, respectively. Finally, constraints (12) - (15) specify the domains of the decision variables: arc activation variables and ticketing variables are binary, service frequencies are nonnegative integers, and fleet size is modeled as a nonnegative integer variable.

4.4 Build and Compute Objective Function

With all cost and revenue parameters defined, the model now possesses the necessary economic and operational inputs to evaluate the performance of each potential service configuration. These parameters serve as the quantitative foundation for constructing the objective functions, which

guide the optimization process by balancing revenue generation against operating expenditures. In the following section, the formulation and computation of these objective functions are presented in detail, outlining how the solver integrates demand, cost, and network structure to identify the most efficient and economically viable service patterns.

4.4.1 Define Parameters

In order to operationalize the mathematical representation of the network, the next step consists of defining the model parameters. Parameters represent the exogenous, fixed input values of the problem that characterize the properties of the railway network and provide the quantitative foundation for optimization. In the context of the present line planning model, four primary categories of parameters are introduced: distance, travel time, ticket price, costs and train capacity.

The distance parameter is denoted as

$$d_{ij} \quad \forall (i, j) \in A,$$

and specifies the physical length of the track segment between two directly connected stations i and j . Similarly, the travel time parameter

$$t_{ij} \quad \forall (i, j) \in A,$$

captures the required time for a train to travel along arc (i, j) , based on the aggregated data extracted from train operator schedules. Ticket prices are represented by

$$c_{ij} \quad \forall (i, j) \in A,$$

indicating the average monetary cost of traveling between two directly connected stations, based on the constructed pricing matrix that accounts for dynamic pricing strategies.

A passenger distribution component is additionally introduced to approximate demand between different stations. This is denoted as

$$p_{ij} \quad \forall (i, j) \in A,$$

where p_{ij} expresses the proportion of passengers traveling from origin i to destination j . The passenger distribution is not based on official volume data but instead derived from the weighted Markov process combining three determinants: travel distance, travel time, and the population-based attractiveness of each destination. To account for their relative importance, weighting factors are applied: distance is weighted with $w_d = 0.8$, time with $w_t = 0.5$, and attractiveness with $w_a = 1000$. This weighting reflects the assumption that passengers primarily choose connections based on the attractiveness of a city (e.g., job opportunities, tourism, cultural pull), while time and distance remain important but secondary considerations.

The total operational cost of a train operating along a route is composed of multiple additive cost components associated with infrastructure usage, vehicle operation, personnel, station stops, and international coordination. For each direct connection (arc) $(i, j) \in A$, the following parameters are defined:

TAC _{ij} :	track access charge per train-kilometer [€/km]
VAR _{ij} :	variable cost per train-kilometer for energy and maintenance[€/km]

STAFF _{ij} :	staff cost per train-hour [€/h]
STOP _{ij} :	station fee applied at the terminal station [€]
BORDER _{ij} :	border-crossing surcharge applied if i and j lie in different countries [€]
FIX:	fixed cost per train run [€]

Each arc-specific cost is then computed as:

$$C_{ij} = d_{ij} (TAC_{ij} + VAR_{ij}) + \frac{t_{ij}}{60} \text{STAFF}_{ij} + \text{STOP}_{ij} + \text{BORDER}_{ij}, \forall (i, j) \in A.$$

Here, d_{ij} and t_{ij} denote the physical distance (in km) and travel time (in minutes) between stations i and j , respectively. The country-specific track access charges are defined as:

$$TAC_{ij} = \begin{cases} 15.52 & \text{if } (i, j) \in \text{Germany,} \\ 1.42 & \text{if } (i, j) \in \text{Austria,} \\ 9.77 & \text{if } (i, j) \in \text{France,} \\ 4.09 & \text{if } (i, j) \in \text{Italy,} \\ 4.85 & \text{if } (i, j) \in \text{Switzerland,} \\ 1.24 & \text{if } (i, j) \in \text{Czech Republic,} \\ 7.00 & \text{otherwise.} \end{cases}$$

The objective function for minimizing total travel time is given as:

$$\min Z_{time} = \sum_{(i,j) \in A} t_{ij} \cdot x_{ij}$$

where t_{ij} denotes the travel time (in minutes) for the segment between stations i and j . As with distance, the binary decision variable x_{ij} determines whether the arc is selected in the route.

The objective function for minimizing total travel distance is given as:

$$\min Z_{dist} = \sum_{(i,j) \in A} d_{ij} \cdot x_{ij}$$

where d_{ij} denotes the distance (in km) between stations i and j , and $x_{ij} \in \{0,1\}$ is the decision variable that indicates whether the connection between stations i and j is used in the final route.

The economic objective is expressed as a profit-maximizing objective function

$$\max \sum_{r \in R} (\text{REV}_r \cdot f_r - \text{COST}_r \cdot f_r),$$

where REV_r denotes the revenue potential of route r and COST_r the total operating cost per rotation. In the implementation, this is represented by maximizing the equivalent term $-\sum_r \text{COST}_r f_r$, with revenues evaluated ex post through the boarding–alighting simulation.

While the single-objective models provide insight into extreme solutions, real-world railway planning requires balancing conflicting objectives. To capture these trade-offs explicitly, the model is

extended to a multi-objective weighted-sum formulation, which is introduced here for the first time in the thesis:

$$\min w_T \sum_{r \in R} T_r x_r + w_D \sum_{r \in R} D_r x_r - w_{\text{Prof}} \sum_{r \in R} \text{Prof}_r f_r$$

The weights w_T , w_D , and w_{Π} control the relative importance of travel time minimization, distance minimization, and revenue maximization, respectively. This formulation enables the generation of compromise solutions that reflect different strategic preferences and allows for a systematic exploration of Pareto-efficient line plans in later chapters.

The total operational cost of a complete train run along a route $R = \{(i_1, i_2), (i_2, i_3), \dots, (i_{n-1}, i_n)\}$ is then given by:

$$C^{\text{run}} = \sum_{(i,j) \in R} C_{ij} + \text{FIX}.$$

If n_{trains} trains operate on this route, the total cost becomes:

$$C^{\text{total}} = n_{\text{trains}} \times C^{\text{run}}.$$

The resulting cost formulation directly corresponds to the structure implemented in the solver code, where all arc-level costs C_{ij} are aggregated to compute the total route cost, which in turn is compared to the boarding-based revenue to determine the operating profit and margin for each benchmark and solver created scenario.

In the final stage of the simulation, the model computes the operational profit of each active route by comparing the total revenue generated through passenger demand with the corresponding operational costs derived from the parameterized cost model. The revenue of a route is obtained dynamically during the boarding–alighting simulation, where each passenger boarding event contributes an incremental revenue equal to the product of the number of passengers and the respective ticket price between origin and destination:

$$R = \sum_{(i,j) \in R} p_{ij} \cdot c_{ij},$$

where p_{ij} represents the number of boarding passengers from station i to station j , and c_{ij} the corresponding ticket price. The operational cost per leg is computed like explained in the previous paragraph. The total route cost is then aggregated over all legs and multiplied by the route frequency (f_r) to yield:

$$C_r = f_r \cdot \sum_{(i,j) \in R} K_{ij}.$$

Finally, the operating profit for each route is determined as the difference between the total revenue and the total cost:

$$\Pi_r = R_r - C_r,$$

and the profit margin is computed as:

$$M_r = \frac{\Pi_r}{R_r} \times 100\%.$$

In the solver output, these values are displayed for each active route as “*Cost per Run*”, “*Cost total*”, “*Profit total*”, and for the network aggregate as “*Total Revenue*”, “*Total Costs*”, and “*Total Profit*”. This enables direct evaluation of both route-level and system-level profitability under the specified objective (minimization of distance or time, or maximization of profit).

Finally, the capacity of a single train is defined as

$$Cap,$$

representing the maximum number of passengers that can be transported per train on the given route. In the present case study, the high-speed train under investigation (ICE-T) is assumed to have a seating capacity of $Cap = 372$. This parameter is critical for ensuring that passenger demand allocations respect the physical limitations of rolling stock and that line planning solutions remain operationally feasible.

Altogether, the defined parameters $(d_{ij}, t_{ij}, c_{ij}, p_{ij}, w_d, w_t, w_a, C, Cap)$ establish the quantitative foundation of the model. They enable the formulation of meaningful objective functions and constraints by systematically translating the physical, temporal, economic, and behavioural properties of the railway system into mathematical terms.

4.4.2 Decision Variables

In optimization models, decision variables represent the endogenous choices to be made by the planner, and they are the central elements that the solver manipulates to minimize or maximize the objective function. In the context of the present line planning model, two main types of decision variables are introduced to capture both the physical selection of routes and the structure of fare segmentation.

The first decision variable is defined as

$$x_{ij} \in \{0,1\} \quad \forall (i,j) \in A,$$

where $x_{ij} = 1$ if the railway line includes arc (i,j) , and $x_{ij} = 0$ otherwise. This binary decision variable directly determines the path chosen through the network by activating or deactivating feasible connections between stations. The complete route from the origin in Turin ($i = 1$) to the destination in Venice ($j = 5$) can therefore be represented as a sequence of arcs for which $x_{ij} = 1$. The values of x_{ij} are later multiplied with the entries from the distance matrix (d_{ij}) and time matrix (t_{ij}) to capture total distance- and time-related costs, as well as with the passenger flow matrix to determine load distribution along the selected arcs.

To account for the ticketing logic of railway operators, where prices may not be additive across all connections but instead reflect segments of the main corridor, a second binary decision variable is introduced:

$$y_{ij} \in \{0,1\} \quad \forall (i,j) \in A,$$

where $y_{ij} = 1$ if a valid ticket segment exists for the connection (i,j) . This variable ensures that pricing along the route follows the appropriate structure: tickets on the legs (e.g., Turin $\rightarrow$ Genua) are treated as single purchase options, whereas deviations onto whole Routes (e.g., Turin $\rightarrow$ Venice) require additive pricing across the involved arcs. The y_{ij} -variables are directly linked to

the cost matrix (c_{ij}) , since the chosen segmentation defines how ticket prices accumulate depending on whether the traveler rides on a specific leg or not.

Together, the decision variables (x_{ij}, y_{ij}) capture both the physical line planning (network design through selected arcs) and the economic dimension of passenger fares (valid ticket segments). Their interaction with the distance, time, cost, and passenger demand matrices ensures that the model not only selects an optimal route but also realistically evaluates operational expenditure, travel time, pricing structures, and passenger allocation. This provides the foundation for building an integrated objective function that balances multiple operator- and passenger-oriented criteria.

4.4.3 Create constraints

Before formulating the constraints, the set of feasible arcs must be explicitly defined. The set of arcs $A \subseteq N \times N$ represents all possible directed links in the network. Its construction is critical because it directly determines the solution space of the line planning problem. In this study, A is generated from two complementary sources:

1. Infrastructure data – the distance matrix extracted from “Parameters” provides the physically existing track connections between stations.
2. Schematic network design – feasible but non-obvious links are included, such as Ingolstadt’s connections to Munich, Augsburg, Regensburg, Nuremberg, and Würzburg, as well as the additional link between Munich and Plattling.

Formally,

Based on this definition, the decision variables x_{ij} and y_{ij} are only introduced for arcs $(i, j) \in A$, ensuring the model remains consistent with both physical infrastructure and operational relevance.

The constraints for the optimization model are then formulated as follows:

1. Flow conservation

$$\sum_{j:(i,j) \in A} x_{ij} - \sum_{j:(j,i) \in A} x_{ji} = \begin{cases} 1 & \text{if } i = O \\ -1 & \text{if } i = D \\ 0 & \text{otherwise} \end{cases}$$

This ensures that the selected path starts at the origin, ends at the destination, and is continuous across intermediate stations without creating breaks or cycles.

2. Uniqueness of route

$$\sum_{j:(O,j) \in A} x_{Oj} = 1, \quad \sum_{(i,D) \in A} x_{iD} = 1$$

Exactly one arc must leave the origin and exactly one must enter the destination, guaranteeing a unique path from start to end.

3. Capacity constraint

$$\sum_{(i,j) \in A} Pas_{ij} \cdot x_{ij} \leq Cap$$

where p_{ij} denotes the estimated passenger volume on arc (i, j) derived from the weighted Markov distribution, and $Cap = 372$ is the maximum train capacity. This ensures that no feasible solution exceeds the physical train capacity, which is essential for operational realism.

4. Passenger distribution consistency

$$\sum_{j:(i,j) \in A} Pas_{ij} = \text{boarding at } i, \quad \sum_{j:(j,i) \in A} Pas_{ji} = \text{alightings at } i,$$

The Markov-based passenger distribution ensures that the aggregated boarding and alighting probabilities across the chosen route sum correctly. Formally, for each station $i \in N$:

This guarantees consistency between the probability model and the actual flow of passengers along the selected route.

5. Fare segment consistency

To reflect pricing policies, ticket segments are encoded through y_{ij} . If the route stays entirely on the main corridor, we require:

$$P_{O,D} = \sum_{(i,j) \in A} p_{ij} \cdot y_{ij}$$

6. Binary decision variables

$$x_{ij} \in \{0,1\}, \quad y_{ij} \in \{0,1\} \quad \forall (i,j) \in A.$$

This enforces the interpretation of x_{ij} as route usage indicators (is the arc part of the line or not) and y_{ij} as ticket segment indicators (is a direct ticket valid on that connection).

These constraints jointly define the feasible solution space of the line planning problem. Flow and uniqueness constraints guarantee a continuous, unambiguous path from the Origin to the Destination. Binary constraints ensure interpretability of variables. Capacity and passenger distribution constraints link infrastructure design to realistic demand flows, preventing oversaturation of train capacity. Fare segment constraints allow the model to calculate the segment costs to an overall Revenue for the whole Route. Together, these conditions yield a mathematically rigorous but operationally meaningful formulation of the corridor line planning problem.

5. Decision Support System for LPP

The modelling framework developed in this thesis can be embedded into a structured Decision Support System (DSS) to assist railway planners in designing and evaluating line plans under multiple, potentially conflicting objectives. The DSS integrates the optimization models, data management, and evaluation procedures into a coherent process that supports iterative, transparent, and reproducible decision-making. Conceptually, the DSS comprises four main components: data and input management, model configuration and scenario generation, solution analysis and visualization, and multi-criteria decision-making.

Parameters Table

A comprehensive Excel-based parameter table serves as the central data source for the entire modeling framework. This master file consolidates all relevant information required for the line planning model, including the travel time matrix, distance matrix, ticket price matrix, and passenger demand distribution. Together, these matrices provide the quantitative foundation for all subsequent calculations performed within the Python environment. The structure ensures that every city pair in the 117-city network is associated with consistent, interlinked parameter values, forming a unified input layer for route evaluation and optimization.

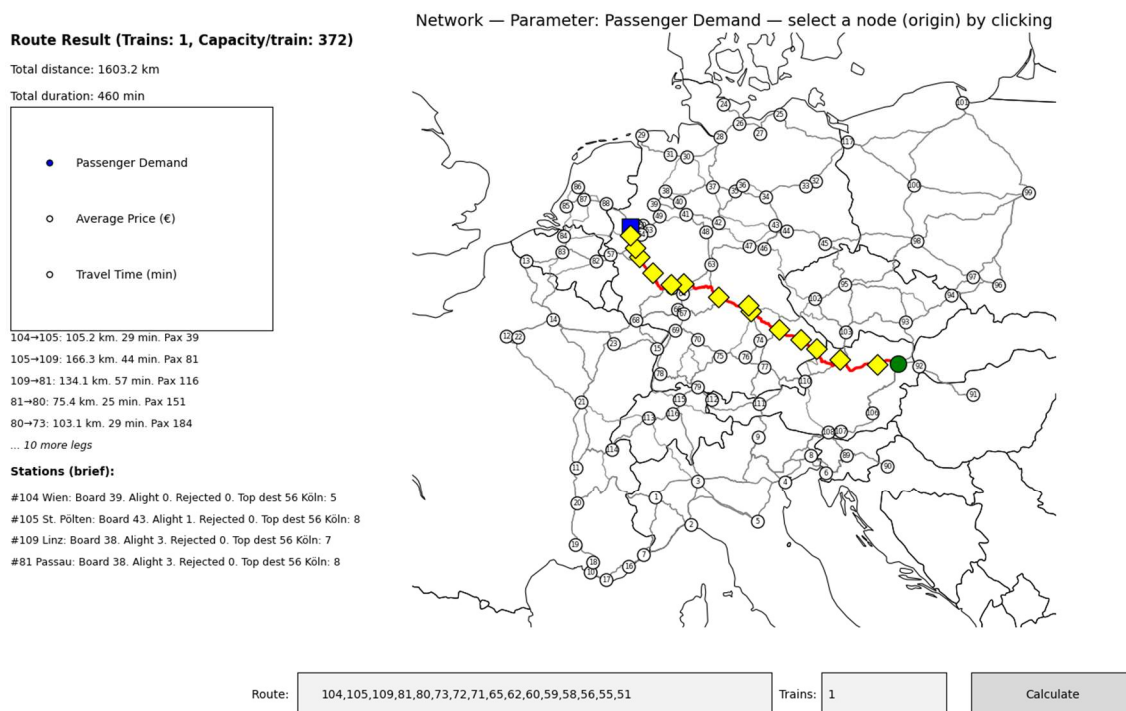


Figure 11: Plot from the code

To visualize and interact with these parameters, an interactive network code was developed in Python using the library tkinter. When executed, this tool allows users to dynamically switch between different information layers - such as travel time, ticket price, and passenger demand - providing an intuitive overview of the underlying data. For the demand matrix in particular, the user first selects the demand category and then a specific city; the visualization then displays the number of passengers originating from that city and traveling to each of the other network nodes. This enables a direct inspection of the spatial distribution of demand and its intensity within the network.

Beyond static exploration, the tool also supports route-based computation. By entering a sequence of city identifiers (e.g., 1–2–3–5–4), the program automatically calculates the corresponding total route distance, travel time, revenue, number of transported passengers, profit, margin and number of declined passengers. These computations form the basis for the benchmark route analyses presented later in this thesis, as they allow the systematic comparison of existing and hypothetical service configurations.

A deeper level of analysis further breaks down these results per station, revealing detailed operational insights such as train occupancy after each stop and whether capacity limits have been reached. This level of granularity relies heavily on the precision of the 117×117 parameter matrices, as even small inaccuracies could propagate through the model and distort key performance metrics. Consequently, the accuracy and internal consistency of the master Excel dataset are essential prerequisites for producing reliable and interpretable results within the Central European line planning problem.

Data and Input Management

The first component of the DSS is responsible for collecting, structuring, and maintaining all relevant input data required by the line planning models. This includes infrastructure data (railway network topology, travel times, distances, and capacity constraints), demand data (origin–destination matrices, time-of-day factors, and passenger segmentation), rolling stock characteristics (train capacity, operating cost, and technical restrictions), and economic parameters (fare structure, variable and fixed cost components).

Within the DSS, these data are stored in a consistent format and linked to the mathematical models through well-defined interfaces. This ensures that updates in demand forecasts, infrastructure changes, or policy parameters can be incorporated efficiently without fundamentally modifying the optimization core. In a practical implementation, this layer can be realized by a database or a structured collection of input files, supported by routines for preprocessing, validation, and consistency checking. By separating the data layer from the optimization logic, the DSS remains flexible and adaptable to future changes in the planning context.

Model Configuration and Scenario Generation

The second component of the DSS concerns the configuration of the line planning models and the generation of planning scenarios. Based on the data layer, planners can specify the modelling horizon, the planning region, and the set of candidate lines. Crucially, they can also configure which objectives are to be prioritized and how they are combined. The framework developed in this thesis supports both single-objective and multi-objective formulations.

In the single-objective setting, the DSS allows the user to select one primary objective, such as minimization of total travel time, minimization of operated distance, or maximization of profit. The system then runs the corresponding mixed integer programming model and returns the optimal line plan under that criterion. In the multi-objective setting, the DSS offers two complementary modes. First, a weighted-sum mode allows the decision-maker to assign explicit weights to different objectives (e.g. profit, time, distance) and to generate a single compromise solution for a given weight vector. Second, a Pareto-based mode explores a range of weight combinations and produces a set of non-dominated solutions that approximate the Pareto frontier.

From a decision-support perspective, both modes are interpreted as scenario generators: a “scenario” is defined by a particular combination of objectives, weights, and constraints (such as minimum coverage conditions or maximum route length). The DSS thus guides the user in systematically exploring different strategic configurations and in understanding how the line plan reacts to changes in preferences or assumptions.

The geographic reference system used throughout the workflow was EPSG:4326 (WGS84), which expresses coordinates in decimal degrees of latitude and longitude. The study area was defined as Central Europe, delimited by a bounding box extending from longitude -1.0° to 22.0° and latitude 42.0° to 56.0° . This extent includes the primary Central European countries such as France, Germany, Switzerland, Austria, northern Italy, the Benelux countries, the Czech Republic, and western Poland.

Solution Analysis and Visualization

Once optimization runs have been completed, the third component of the DSS provides tools for analysing and visualizing the resulting line plans. The goal is to convert the raw model output (flows, binary line activation variables, and objective values) into information that is accessible to both technical and non-technical stakeholders.

On the quantitative side, the DSS computes a set of performance indicators for each line plan, including total profit, revenue, and operating cost; average and maximum travel times; total operated distance; capacity utilization; and measures of spatial coverage or connectivity. These indicators allow for a systematic comparison between scenarios, such as contrasting the pure profit-maximizing solution with more balanced multi-objective alternatives. Additionally, route-level metrics (e.g. per-line profit, distance, travel time, and load factor) provide detailed insight into which lines drive the overall performance.

On the spatial side, the DSS can visualize the selected lines on a network map, highlighting route alignments, frequency, and direction. Differences between scenarios - such as the shift from regional, short-distance lines toward long-distance international corridors - can thus be inspected visually. For multi-objective analyses, scatter plots or parallel coordinate plots of the objective values and key indicators can be used to illustrate the trade-offs between profit, time, and distance. Together, these analytical and visualization tools enable the decision-maker to identify structure, strengths, and weaknesses in each candidate line plan.

To translate the theoretical line planning model into a functional computational framework, a comprehensive Python-based solver was developed. This solver integrates geospatial data processing, network generation, optimization, and simulation within a unified workflow. Its purpose is to identify optimal train routes and service frequencies across a pre-defined set of Central European cities while adhering to technical and operational constraints such as fleet size, maximum route length, and passenger demand.

The implementation combines several specialized Python libraries - GeoPandas for spatial representation, NetworkX for network topology construction, PuLP for mixed-integer optimization, and Matplotlib for visualization - enabling a transparent and flexible analysis environment. By automating each stage of the modeling process, from data import and route generation to revenue simulation and map-based visualization, the tool ensures both reproducibility and scalability.

This integrated approach allows the exploration of different optimization objectives - such as minimal total travel time, minimal distance, or maximal total revenue - and provides an analytical foundation for evaluating strategic line planning decisions in large-scale rail networks.

At the beginning of the code, all cities included in the modeled rail network are manually defined as a list of tuples. Each tuple contains the city's name, longitude, and latitude, which together provide the geographic foundation for spatial modeling. These coordinates are used later for both route calculations and geospatial visualization. In addition, each city is automatically assigned a unique numerical identifier ranging from 1 to N (where N equals the total number of cities in the network). This indexing ensures consistent referencing of cities across all data structures, including the distance, time, price, and passenger matrices.

The model employs the GeoPandas and Matplotlib libraries to visualize the network. A bounding box covering Central Europe defines the spatial extent of the plot, while a shapefile from Natural Earth provides the political boundaries of countries. Each city is converted into a GeoDataFrame object with its coordinates represented as geometric points. This geographic layer is later used to plot the overall rail network and highlight specific optimized routes. The function `draw_geo_network()` takes care of this process: it plots all cities and connections, optionally highlighting one optimized route in red for better visual interpretation.

The function `load_network_from_excel()` handles the import of all necessary input data from a central Excel file called `Parameters.xlsx`.

This file contains multiple sheets corresponding to different matrices:

- Passenger Spread (origin–destination demand in passenger numbers)
- Distance Matrix (inter-city distances in kilometers)
- Time Matrix (travel times in minutes)
- Price Matrix (average ticket prices between cities)
- and a list of direct connections (edges) between cities.

The helper function `load_matrix_from_sheet()` reads each matrix and ensures that rows and columns are correctly aligned with the predefined city indices. This alignment guarantees data consistency, as the Excel file uses the same numbering system as the in-code city definitions.

To allow flexible scenario testing, the program integrates a Graphical User Interface (GUI) built with the Tkinter library.

Through this GUI, users can define key model parameters such as:

- total fleet size (number of available trains),
- minimum and maximum number of routes to be generated,
- minimum and maximum number of stops per route,
- maximum total travel time per route,
- and the optimization target (either minimal travel time, minimal distance, or maximal revenue).

Additionally, users can limit the maximum number of trips per route in order to prevent the solver to run the optimal route several times without considering alternative or next best routes. The GUI

ensures that all relevant parameters are entered before execution, making the system accessible without modifying the code (Figure 12).

The exploration of the railway network is now performed using a k-shortest-paths based algorithm, replacing the former random-walk approach. Instead of generating thousands of random routes, the system builds a NetworkX graph from all cities and their direct connections and computes, for each relevant city pair, up to k shortest simple paths based on travel time.

Figure 12: GUI Solver

This is achieved using the `networkx.shortest_simple_paths()` generator, which returns simple (loop-free) routes ordered by increasing travel time. Only the first k such paths are evaluated. Each candidate path is then filtered to ensure it satisfies the global constraints: the maximum allowed travel time (`max_time`) and the permitted range of stops (`min_stops` to `max_stops`).

This method yields a compact yet highly relevant set of high-quality route candidates, dramatically reducing the search space while capturing the most meaningful alternatives for optimization. Duplicate routes are inherently avoided due to the structure of the k-shortest-paths algorithm, ensuring an efficient and deterministic generation of candidate train services.

Once all potential routes are generated, the model formulates a Mixed Integer Linear Programming (MILP) problem using the PuLP optimization package.

The model computes several route-specific attributes, including total distance, total travel time, total revenue, and a revenue potential score derived from ticket prices and passenger capacity. In addition, it evaluates operational profit, profit margin, and detailed costs per leg, providing a comprehensive assessment of each route's economic performance. The model also tracks passenger changes at each station, indicating boarding and alighting volumes along the corridor, as well as the occurrence of border crossings, which influence overall operational complexity and cost. Depending on the user's selected objective, the solver then either minimizes total travel time or total distance, or maximizes total revenue, thereby aligning the optimization outcome with the desired performance criterion.

Constraints ensure operational feasibility:

- the total number of active routes lies between the specified minimum and maximum;
- total assigned frequencies do not exceed available fleet size;
- route frequencies remain consistent with fleet and time constraints.

To prevent trivial or "empty" solutions (where no routes are selected), the model introduces an artificial penalty term that discourages inactive networks. This guarantees that the solver always activates at least the minimum required number of routes. Without this constraint, an optimization solely focused on minimizing travel time or distance would converge toward a degenerate solution - effectively selecting no stops or connections at all - as this would mathematically represent the lowest possible objective value.

After the optimization step, the model transitions into a simulation phase designed to evaluate both the operational and financial performance of each active route. For every selected route and each scheduled trip, the simulation tracks the number of passengers boarding, alighting, and remaining on board at each station stop. A dynamic passenger load is maintained throughout the trip to ensure that onboard occupancy never exceeds the predefined train capacity of 372 seats. Revenue accumulation is computed incrementally at each station as the product of the number of boarding passengers and their respective ticket price between origin and destination. The program outputs a detailed table for each trip, listing the station name, number of boarding and alighting passengers, the current onboard load, and the cumulative trip revenue.

Beyond revenue analysis, the model also calculates route-specific operational costs, total profit, and profit margins by integrating the predefined cost parameters (track access, energy, staff, station, and border fees) into the simulation results. This allows for a comprehensive financial evaluation of each route, comparing revenues to their corresponding cost structures on a per-leg and per-trip basis. The code additionally reports cost per leg, total route cost, and overall profit or loss for each connection, thus providing direct insight into the economic viability of different network configurations.

After all trips are simulated, the program aggregates key performance indicators across the entire system, including:

- total travel time,
- total traveled distance,
- total generated revenue,
- total operating cost, and
- total profit and profit margin.

It also identifies the most active route (based on frequency, passenger turnover, and revenue contribution), which is highlighted in the geospatial visualization that follows. All results are printed in a structured summary, enabling a clear interpretation of both the operational efficiency and financial sustainability of the optimized line plan.

The final visualization component uses Matplotlib and GeoPandas to generate a map of the full network. All connections are drawn as grey lines, while the optimal route identified during the simulation is displayed prominently in red, with start, intermediate, and terminal stations marked in distinct colors. This visualization serves as an intuitive interpretation tool, illustrating the spatial distribution and connectivity of the optimized rail lines within Central Europe. It provides a clear link between quantitative model outputs and the geographic realities of the transport network.

In summary, the Line Planning Solver integrates geographic, operational, and economic dimensions of railway network design into a single analytical workflow. By combining route generation, mathematical optimization, passenger simulation, and visual analysis, the model supports data-driven decision-making for strategic rail planning. Its modular design allows researchers and planners to easily adjust parameters, explore alternative objectives, and visualize outcomes directly - thereby making it a powerful tool for understanding trade-offs between efficiency, coverage, and profitability in intercity rail networks.

The final component of the DSS supports the actual decision-making process by structuring how model results are evaluated against broader policy and stakeholder objectives. While the optimization models generate mathematically efficient solutions under specified objectives and constraints, the ultimate choice of a line plan must incorporate additional considerations such as political priorities, equity concerns, environmental objectives, or implementation feasibility.

Within the DSS, the set of candidate solutions (particularly those obtained from the Pareto-based multi-objective analysis) is treated as a menu of efficient options. Decision-makers can then apply qualitative and quantitative multi-criteria decision-making (MCDM) procedures to select a preferred solution. Quantitative approaches may involve scoring or ranking candidate plans using additional criteria (e.g. robustness, regional accessibility, or alignment with regulatory requirements), which are not necessarily included in the optimization model but can be evaluated ex post. Qualitative assessments may involve expert judgement, stakeholder workshops, or policy deliberations, in which the trade-offs made by different solutions are discussed.

The key contribution of the DSS in this step is transparency: by explicitly presenting the trade-offs between travel time, distance, and profit, and by linking them to spatial and operational characteristics of the network, the system supports informed, defensible choices. In particular, it highlights that the extreme single-objective solutions (e.g. pure time or profit optimization) may be unattractive from a policy standpoint, whereas intermediate multi-objective solutions may offer a more acceptable balance between efficiency and service quality.

Integration into the Planning Process

Taken together, these components form a coherent DSS that fits into the broader strategic and tactical planning cycle of a railway operator. Strategically, the system can be used to explore long-term network design options and to examine the implications of new infrastructure or policy constraints. Tactically, it can support the refinement of line plans for specific timetable periods, enabling planners to adjust line structures as demand, costs, and policy priorities evolve.

The DSS thus operationalizes the modelling work of this thesis: it transforms the line planning problem from a one-off optimization exercise into an iterative, interactive process in which planners can explore scenarios, understand trade-offs, and align the final line plan with economic, operational, and policy objectives. This framework can be extended in future research by integrating more detailed capacity and timetable models, stochastic demand representations, or explicit environmental targets, thereby further enhancing its usefulness as a comprehensive decision support tool for railway line planning.

6. Results and Discussion

To operationalize the proposed line planning framework, the model is implemented in Python 3.12 using a combination of established optimization, network-analysis, and visualization libraries. The line planning problems are formulated as mixed-integer linear programs and solved using PuLP as the modeling interface, with the CBC solver employed as the primary optimization backend. Network representation and path generation are handled using NetworkX, while data preprocessing and parameter management (e.g., distance, travel time, fare, cost, and passenger-demand matrices) are conducted using pandas and NumPy. Spatial operations and infrastructure-based route construction rely on GeoPandas, Shapely, and PyProj, enabling the integration of geographically realistic railway paths. Visualization of network structures, selected line plans, and

optimization outcomes - including Pareto frontiers and passenger load distributions - is performed using Matplotlib, with optional interactive elements implemented via Tkinter for graphical user interaction. All computational experiments were executed on a personal workstation equipped with an Intel Core i7 processor, 32 GB RAM, and a Windows 10 (64-bit) operating system, ensuring sufficient computational resources for large-scale network instances and multi-objective scenario analyses.

6.1 Benchmark Routes

Within the context of the Central European rail network, a crucial step in the line planning process is the identification of a representative set of feasible routes. Although the optimization model ultimately determines which train lines best satisfy passenger demand - including which stations are served or bypassed and how often each line operates - it cannot do so efficiently without a well-structured and realistic search space. Given the scale and heterogeneity of the system, it is essential to define connections that reflect realistic passenger demand patterns and operational constraints while maintaining computational tractability for optimization. The network is charac-

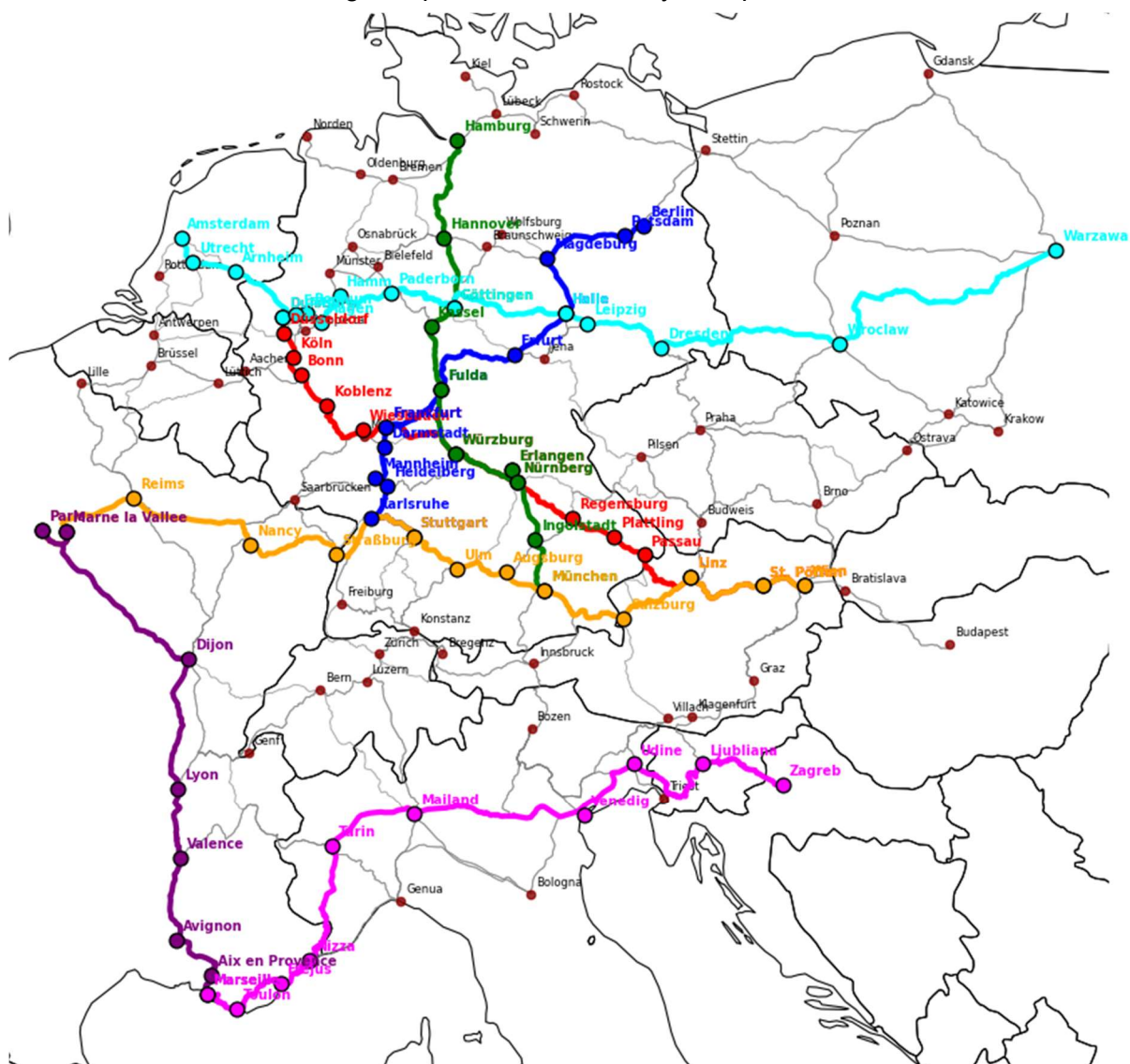


Figure 13: Illustration of Benchmark Routes

terized by strong east–west and north–south flows linking major metropolitan areas such as Paris, Berlin, Vienna, Budapest, and Milano, creating a complex interplay between international corridors and regional feeder lines.

For the purpose of this study, seven benchmark routes have been selected, all of which are currently operating services within the Central European network. Together, these routes cover 71 of the 117 cities included in the dataset, corresponding to a network coverage of approximately 60.7%. This selection provides a representative cross-section of the system, encompassing both international trunk lines and key national corridors, while ensuring that the analysis remains computationally feasible and practically relevant. The selected routes are designed to capture a diverse set of operational and geographical characteristics:

- The first route connects Vienna to Duisburg via Linz, Nuremberg, Frankfurt, Cologne, and Düsseldorf, representing a major east–west corridor through southern Germany.
- The second runs from Berlin to Stuttgart, linking central German and capital regions through Magdeburg, Erfurt, Frankfurt, and Mannheim.
- The third follows a north–south axis from Hamburg to Salzburg, passing through Hannover, Kassel, Würzburg, and Munich.
- The fourth extends from Paris to Vienna, covering Straßburg, Stuttgart, Ulm, Munich, and Linz, and exemplifying a key transnational high-speed connection.
- The fifth is a domestic French route linking Paris and Marseille via Lyon, Valence, and Avignon, illustrating a mature high-speed corridor within Western Europe.
- The sixth connects Marseille to Zagreb, traversing Nice, Turin, Milano, Venezia, Udine, and Ljubljana, representing a southern transalpine connection.
- The seventh and final route runs from Amsterdam to Warszawa, crossing Ruhrgebiet cities such as Essen and Duisburg before continuing eastward through Leipzig, Dresden, Wrocław, and into Poland.

Each of these routes has been highlighted in different colours (red, blue, green, orange, purple, magenta, and cyan) to visually distinguish them within the Central European network map. Collectively, they form a comprehensive benchmark set that reflects both the spatial diversity and the operational realities of long-distance rail services in the region.

The defined route set therefore serves as a foundation for the subsequent analysis, providing a consistent framework for benchmarking and evaluating different line planning strategies across the Central European network. These benchmark routes capture the essential structural and spatial characteristics of the system, enabling a systematic comparison of planning outcomes under varying assumptions and objectives.

The reported results were generated by applying a solver-based mixed-integer linear programming (MILP) model to each benchmark route individually. For every benchmark corridor, the underlying railway network was represented as a directed graph, and the solver selected a feasible path between the predefined origin and destination stations subject to flow conservation and capacity constraints. Passenger flows were assigned to the selected route based on the corresponding origin–destination demand matrix, assuming direct travel without transfers and a homogeneous train capacity. Revenues were calculated as the product of assigned passenger volumes and average OD-specific ticket prices, while operating costs were derived from distance- and time-dependent cost parameters associated with the selected route. For benchmarking purposes, exactly one train service per route was assumed, which isolates structural route performance from frequency effects and ensures comparability across corridors. The optimization itself was conducted using a single-objective formulation minimizing total travel time, subject to feasibility constraints, reflecting the operational objective of identifying the fastest infrastructure-feasible connection between the benchmark endpoints. Based on the resulting route structure, all economic indicators including total revenue, total cost, and profit were subsequently computed in a post-processing step. This procedure ensures that performance differences across benchmark routes

arise solely from network structure, demand distribution, and infrastructure characteristics, rather than from differing service intensities or fleet allocations.

6.1.1 Vienna – Duisburg

The first benchmark route (red) connects Vienna with Duisburg, linking major intermediate hubs such as Linz, Nuremberg, Frankfurt, Cologne, and Düsseldorf. The route covers a total distance of 1603.2 km and a total travel time of 460 minutes. According to the solver results, a total of 747 passengers were transported, generating a total revenue of approximately 61,945€ based on the boarding model. The total cost amounted to 24,751.0€, resulting in an operating profit of 37,194.0€ and an operating margin of 60.0%. Importantly, 1,856 passengers were rejected, suggesting that actual demand surpassed the capacity assumed in the model. (Appendix 1).

The segment-level data show a steady increase in passenger volumes along the east–west axis. Starting with 268 passengers between Vienna and St. Pölten, the number rises continuously through Linz, Passau, and Regensburg, reaching maximum capacity on the key section between St. Pölten and Bonn. This identifies the central German corridor as a major demand cluster. Toward the western end of the route, the passenger count gradually decreases – with 228 passengers between Cologne and Düsseldorf and only 117 passengers on the final leg to Duisburg. This decline likely reflects the dense regional service offer within the Rhine-Ruhr metropolitan area, where passengers have multiple alternative connections.

The last two columns of the per-leg results provide information on the operational cost incurred for each route segment and whether a border crossing occurred. The “Cost leg (€)” column represents the segment-specific cost allocation, reflecting distance-dependent and operational expenses such as energy consumption, crew costs, and infrastructure usage fees. The “Border?” column indicates whether the respective leg crosses an international boundary, with a boolean value (“True” or “False”). In the present case, only one segment - Linz to Passau - triggers a “True” flag, marking the crossing from Austria into Germany. This information is relevant for identifying cost variations potentially influenced by international operations, regulatory differences, or additional handling requirements at border transitions.

At the station level, Vienna remains the primary origin, contributing 268 boardings with no alightings. Other notable boarding locations include St. Pölten (107), Frankfurt (66), Bonn (60), Wiesbaden (39), and Koblenz (39), illustrating a broad spread of demand along both the Austrian and German sections of the route. Alightings are concentrated in Cologne (171), Düsseldorf (125), and Frankfurt (65), consistent with their roles as major interchange or terminal hubs.

A significant share of demand could not be accommodated: a total of 1,856 passengers were rejected. Rejections begin at St. Pölten (178) and continue across most intermediate stations, peaking in the Austrian–Bavarian segment (e.g., Linz 252, Passau 246, Plattling 235). These values indicate that train capacity was consistently saturated for much of the journey.

Overall, the first benchmark route continues to show a strong east–west demand pattern, with passenger volumes rising sharply through central Germany - particularly between Nuremberg, Würzburg, and Frankfurt. The service successfully links Austria’s capital with several major German economic and population centers, underscoring its importance for both international and interregional mobility.

However, the updated results reveal substantial capacity pressure along the corridor: 1,856 passengers were rejected, with rejections occurring consistently from St. Pölten onward. This indicates that demand regularly exceeds available capacity, especially within the Austrian–Bavarian

section and the approach to central Germany. Rather than a balanced load profile, the route now demonstrates clear saturation effects, highlighting the need for adjusted rolling-stock provision or timetable planning.

As the first analyzed route, it nonetheless remains a valuable reference case for long-distance, cross-border rail planning, offering a baseline for evaluating how different planning strategies - such as capacity upgrades, frequency adjustments, or demand steering - may affect performance, capacity allocation, and passenger distribution across the Central European network.

6.1.2 Berlin – Stuttgart

The second benchmark route connects Berlin with Stuttgart across ten intermediate stops, linking major cities such as Potsdam, Magdeburg, Halle, Erfurt, Fulda, Frankfurt, Darmstadt, Mannheim, Heidelberg, and Karlsruhe. Spanning 1,228.1 km with a total travel time of 478 minutes, the route forms a long north–south axis through Germany’s central high-speed network (Appendix 2).

The solver results indicate 733 passengers carried and a total revenue of €52,994 under the boarding-based model. In contrast, 427 passengers were rejected, demonstrating that demand exceeded available capacity on several segments of the corridor. Despite these rejected passengers, the service achieves a positive operating outcome: with total operating costs of €23,320, the route records an operating profit of €29,674 and an operating margin of 56%. No border crossings occur on this domestic connection.

Passenger volumes increase strongly from Berlin into the central German segments. The number of passengers on board rises from 166 between Berlin and Potsdam to 373 between Magdeburg and Halle—the busiest section of the route. High onboard levels continue southward through Erfurt and Fulda before gradually declining toward Stuttgart, falling to 218 on the final leg between Karlsruhe and Stuttgart. Rejections occur predominantly in the northern and central parts of the corridor, with the highest values at Magdeburg (110), Halle (121), and Erfurt (101), reflecting sustained over-demand in these segments.

Revenue exhibits a similar pattern. Early segments generate moderate costs (e.g., €1,027 between Berlin and Potsdam), while revenue peaks at the beginning, such as €19,861 on the Berlin–Potsdam leg. Earnings taper off near the southern terminus as onboard volumes decrease.

At the station level, Berlin is the primary origin with 166 boardings, followed by steady additional inflows at Potsdam (179), Magdeburg (52), Halle (45), and Erfurt (30). Fulda, Frankfurt, Darmstadt, Mannheim, and Heidelberg collectively contribute smaller passenger additions while also serving as major alighting points, particularly in the southern portion of the route. Rejections follow the same spatial pattern as the onboard maxima - concentrated in central Germany and declining toward the south, where capacity becomes less constrained.

Overall, the Berlin–Stuttgart route illustrates a domestic long-distance corridor dominated by strong central-network demand, especially between Magdeburg and Fulda. Unlike the first benchmark route, which experienced heavy international and cross-border flows, this corridor shows a distinctly national pattern with pronounced clustering around Germany’s core nodes. The presence of rejected passengers underscores capacity shortages in the most heavily used segments, yet the route remains profitable under the modeled assumptions due to robust passenger volumes and revenue concentration in central Germany.

Together with the Vienna–Duisburg corridor, this second route provides a complementary perspective within the Central European line-planning framework, highlighting how demand concentration, capacity constraints, and regional cost structures differ across long-distance services.

6.1.3 Hamburg – Salzburg

The third benchmark route links Hamburg in northern Germany with Salzburg at the Austrian border, forming a major north–south spine through central and southern Germany. Along the way, the service connects several important intermediate hubs, including Hannover, Göttingen, Kassel, Fulda, Würzburg, Erlangen, Nuremberg, Ingolstadt, and Munich. The total route length amounts to 1,398.7 km, and the modeled journey time is 358 minutes, placing this connection among the faster long-distance axes relative to its length within the benchmark set.

According to the solver results -based on a single train operating along the corridor -a total of 661 passengers were transported, generating €50,139 in revenue under the boarding-based model. 389 passengers were rejected, indicating that demand consistently exceeded available capacity, particularly in the central portion of the route. Despite these capacity constraints, the service remains financially viable: operating costs total €26,388, resulting in an operating profit of €23,751 and an operating margin of 47.4%. The final leg between Munich and Salzburg is marked as a border-crossing segment, the only one along the route.

Passenger volumes increase sharply from Hamburg toward central Germany. The onboard count rises from 168 passengers between Hamburg and Hannover to 372 between Göttingen and Kassel—the busiest part of the line. High occupancy persists southward through Fulda and Würzburg, with passenger numbers remaining above 350 until Ingolstadt. Only in the final section do volumes drop significantly, reaching 89 passengers between Munich and Salzburg. Rejections follow a similar geographical pattern: they begin at Göttingen (65), peak around Kassel (102) and Fulda (95), and gradually decrease toward the southern terminus.

Revenue distribution mirrors these demand dynamics. Early segments such as Hamburg–Hannover (€18,968) and Hannover–Göttingen (€15,537) generate the highest income, while shorter or less densely used legs (e.g., Erlangen–Nuremberg) produce lower revenue. The highest cost levels correspond to the longest segments, including Hamburg–Hannover and Munich–Salzburg.

At the station level, Hamburg serves as the dominant origin point with 168 boardings, followed by substantial inflows at Hannover (152), Göttingen (81), Kassel (28), and Fulda (26). These early and central stations also exhibit notable rejection levels, indicating persistent over-demand. The heaviest alightings occur in Munich (272), reinforcing its role as the main southern interchange node prior to the Austrian border. Erlangen, Nuremberg, and Ingolstadt show balanced boarding and alighting activity typical of high-frequency corridors that serve both long-distance and regional travel needs.

Overall, this route demonstrates a markedly unbalanced but structurally coherent demand profile: passenger numbers rise steadily toward central Germany, remain at peak levels across the busiest nodes, and decline as the service approaches Salzburg. Compared to the earlier benchmark routes, the Hamburg–Salzburg corridor exhibits strong domestic demand concentration, with the majority of high-traffic sections located well within Germany. While the line includes an international terminus, cross-border operations represent only a fraction of total activity. The presence of rejected passengers highlights the need for additional capacity or adjusted service planning in

central Germany, where utilization is highest. Nevertheless, the service achieves profitable operation under the modeled assumptions, offering a realistic and economically viable candidate for integrated line-planning optimization.

Together with the previous benchmark cases, this north–south axis contributes essential insights into demand distribution, capacity shortages, and revenue potential across Central Europe's long-distance network, forming a key reference point for subsequent optimization scenarios (Appendix 3).

6.1.4 Paris – Vienna

The Paris–Vienna connection represents one of the longest and most internationally significant route within the benchmark set. Extending over 2,064.1 km with a total travel time of 618 minutes, the service links France, Germany, and Austria, thereby crossing some of Europe's busiest long-distance transport corridors. Along its path, the train passes through a sequence of major metropolitan regions, including Reims, Nancy, Strasbourg, Stuttgart, Munich, and Linz, forming a continuous trans-European axis that integrates key political, economic, and cultural centers (Appendix 4).

The solver results for a single train operating along the full corridor indicate substantially higher activity levels than in the earlier scenario: 790 passengers were transported, generating a total boarding-based revenue of €85,081. At the same time, 1,058 passengers were rejected, demonstrating that demand exceeded available capacity across multiple sections of the route - particularly within Germany - resulting in heavy saturation. Despite these rejected passengers, the service exhibits a strong financial outcome. Total operating costs amount to €26,937, while operating profit reaches €58,144, yielding an operating margin of 68.3%. These results reflect the high revenue potential of a densely used, multi-country long-distance corridor, even in the presence of substantial capacity constraints.

Passenger volumes follow a distinct west–east accumulation pattern. The service begins in Paris with 239 boardings, after which additional inflows at Marne-la-Vallée, Reims, and Nancy steadily increase the onboard totals. A notable surge occurs upon entering Germany at Strasbourg (373 onboard after stop), after which the load remains at or near the train's effective capacity ceiling (≈ 370 passengers). Central German nodes - including Stuttgart, Ulm, Augsburg, and Munich - constitute the strongest demand drivers. Munich in particular acts as the dominant redistribution hub, with 106 alightings, marking the most significant passenger turnover along the route. After crossing into Austria, volumes decline gradually, with Salzburg, Linz, and St. Pölten contributing moderate exchanges before the train reaches Vienna with 313 onboard.

The boarding pattern displays a clearly cumulative structure, typical for long international routes. Early French stations generate substantial revenues (e.g., €44,522 in Paris, €18,968 in Marne-la-Vallée), while the German section produces the highest combined revenue volumes and the strongest concentration of both boardings and alightings. Rejected passenger levels follow the same spatial distribution: they begin in Marne-la-Vallée (106 rejected), increase sharply in Reims (227) and Nancy (212), and Stuttgart (109) and Ulm (133), before gradually declining toward Austria.

Compared with the nationally confined benchmark routes, the Paris–Vienna service exemplifies a genuinely trans-European long-distance corridor, requiring operational harmonization across three national railway systems. The route's demand profile - with cumulative inflows feeding into

a sustained long-distance core segment - highlights its strategic importance for cross-border mobility. The high operating margin suggests that even modest enhancements in capacity or timetable design could significantly improve efficiency, reduce rejected demand, and further strengthen financial performance.

From a line-planning standpoint, the Paris-Vienna connection highlights the complexities that arise when a single service spans several national rail systems. The consistently high demand - often surpassing available capacity - shows that well-linked international corridors can generate substantial economic returns, provided that the underlying interregional flows are strong. As such, this route serves as a key example for examining how cross-border capacity should be allocated, how rolling stock must be dimensioned for multinational operations, and how long-distance services can be structured across the broader Central European rail network.

6.1.5 Paris – Marseille

The Paris–Marseille benchmark route represents one of France's most emblematic domestic high-speed connections, linking the capital with the Mediterranean coast via Dijon, Lyon, Valence, Avignon, and Aix-en-Provence. Covering 1,315.1 km in 369 minutes, the service follows the LGV Sud-Est and LGV Méditerranée - two of Europe's oldest, busiest, and most technically advanced high-speed corridors. As such, the route provides a mature example of long-distance, high-frequency HSR operations fully contained within a single national system (Appendix 5).

According to the solver output for a single train operating the full corridor, a total of 486 passengers were transported, generating €41,798 in boarding-based revenue. As in other French domestic cases, the model reported zero rejected passengers, confirming that available capacity was more than sufficient for the modeled demand. With total operating costs of €16,906, the route achieves an operating profit of €24,892, corresponding to an operating margin of 59.6%. This positive financial result makes the Paris–Marseille line one of the most profitable among the benchmark set, driven by strong domestic demand and efficient long-distance operations.

Passenger volumes follow a distinctly southbound progression. The route starts with 112 passengers departing Paris and grows steadily through Marne-la-Vallée (214 onboard after the stop) and Dijon (287). The central section between Dijon, Lyon, and Valence forms the demand peak, with more than 279–288 passengers consistently on board. South of Valence, ridership remains robust but gradually declines, with 230 passengers recorded on the final Aix-en-Provence–Marseille segment as the train approaches its terminus.

South of Lyon, boarding flows taper, while alightings increase - particularly in Valence (42 alightings) and Avignon (58 alightings), reflecting the route's role in connecting both long-distance and strong regional markets. As in all previous French segments, no rejected passengers occur at any station.

This benchmark route stands out for its domestic focus and operational simplicity, without the complications of cross-border coordination that characterize several other long-distance services in the study. Passenger demand is strong and evenly distributed along the main urban centers of the Rhône Valley, illustrating the effectiveness of France's high-speed network design: a limited number of strategically located stops providing broad territorial access.

In contrast, the Paris-Marseille corridor demonstrates what effective line planning can look like within a strictly national high-speed rail environment. Here, the uniform infrastructure and regulatory framework allow the service to operate with consistently high load factors and without any

capacity shortages, resulting in a notably strong operating margin. This route therefore acts as an internal benchmark for the French HSR system, illustrating how cohesive domestic planning and infrastructure integration can translate into both stable ridership and solid financial performance.

6.1.6 Marseille – Zagreb

The second-to-last benchmark route represents one of the most extensive and geographically diverse connections in the analyzed network, linking Marseille on the French Mediterranean coast with Zagreb, the capital of Croatia. Spanning 1,850.6 km with a total travel time of 1,074 minutes, this line crosses four countries - France, Italy, Slovenia, and Croatia - and connects major metropolitan centers such as Nice, Turin, Milan, Venice, and Ljubljana. As a result, it functions not only as a long-distance service but also as a complex, multi-jurisdictional corridor integrating several national railway systems (Appendix 6).

According to the solver-based simulation of one train operating along the full corridor, the route carried 687 passengers and generated €49,161 in boarding-based revenue. The model registered 273 rejected passengers, indicating that capacity was insufficient along certain sections - particularly in Italy - where the load repeatedly approached or reached saturation. Despite these rejected passengers, the service achieves an operating profit of €28,899, with total operating costs of €20,262, resulting in an operating margin of 58.8%. The route includes multiple border crossings - between France and Italy, Italy and Slovenia, and Slovenia and Croatia - which contribute to the corridor's operational complexity.

Passenger volumes follow a clear west–east progression. The line begins in Marseille with 153 passengers, and volumes increase steadily along the French and Italian Riviera, reaching a sustained peak upon entering Italy. Between Fréjus, Nice, and Turin, the train operates near full capacity (e.g., 371–372 passengers on several legs), with the Nice–Turin segment representing one of the busiest parts of the entire benchmark set. After Turin, demand remains high toward Milan, where occupancy still exceeds 300 passengers. East of Venice, however, demand gradually declines as the train enters less densely populated regions, dropping to 236 passengers on the final Ljubljana–Zagreb segment.

Station-level activity highlights several key nodes.

- Marseille functions as the principal point of origin, with 153 boardings generating €15,077 in revenue.
- Toulon and Fréjus add substantial inflows (185 and 49 boardings, respectively).
- Nice marks the beginning of strong cross-border travel flows, with 28 boardings and significant alightings eastward.
- Turin and Milan serve as major interchange hubs within Italy: 68 boardings in Turin and 67 in Milan, combined with high alighting activity, reflect their roles as both intermediate destinations and long-distance connectors.
- Venice, Udine, and Ljubljana show a more regionally dispersed pattern, with both boarding and alighting levels tapering toward the Croatian border.

The presence of 273 rejected passengers, particularly concentrated in the French-Italian and Italian core segments, indicates persistent demand pressure. The Marseille-Zagreb case thus illustrates how an international and highly polycentric corridor can generate strong peak loads that exceed the available supply of seats.

In contrast to the more domestically concentrated French and German benchmarks, this trans-Mediterranean route operates across widely varying infrastructure standards and national systems. Its pronounced demand peak in Italy and its gradual decline toward Slovenia and Croatia highlight the heterogeneity of long-distance travel flows across Southern Europe. Nevertheless, the corridor remains strategically important, as it connects dense Western European travel markets with emerging Southeastern European regions.

Viewed through a line-planning lens, the Marseille-Zagreb connection embodies the operational and strategic challenges of running a service through four distinct national networks. Although the route proves profitable in the model, the notable number of rejected passengers - especially in high-demand stretches - suggests that the existing capacity is insufficient in certain segments. This makes the corridor a clear candidate for targeted interventions such as deploying larger trainsets, adjusting service frequency, or redistributing capacity to better accommodate the heavy demand found in the western and central sections of the journey.

6.1.7 Amsterdam – Warszawa

The seventh and final benchmark route constitutes the most extensive and geographically wide-reaching connection within the analyzed network. Running from Amsterdam in the Netherlands to Warsaw in Poland, the corridor covers 2,371.7 km with a total travel time of 964 minutes. It spans three countries the Netherlands, Germany, Poland and links several major metropolitan areas, including Utrecht, Duisburg, Essen, Bochum, Leipzig, Dresden, Wrocław, and Warsaw. As such, it bridges the dense economic clusters of Western Europe with the emerging long-distance travel markets of Central and Eastern Europe (Appendix 7).

The solver-based results show that a single train operating along the entire corridor carried 753 passengers, generating €92,553 in revenue under the boarding-based model. Notably, the route exhibits substantial capacity shortages, with 1,753 rejected passengers concentrated largely within Germany's high-demand sections. Despite these constraints, the route is both operationally and financially successful: with total operating costs of €37,245, the service yields a significant operating profit of €55,308, corresponding to a strong operating margin of 59.8%.

Passenger volumes rise sharply on the western and central segments of the route. The train departs Amsterdam with 259 passengers, already indicating strong cross-border demand, and load levels increase further through Utrecht, where an additional 120 passengers join the service, and Arnhem, which contributes 9 more, resulting in onboard totals of 370 at both stations. From there, the train reaches maximum occupancy across the German core. The Ruhr area - particularly the segments between Duisburg, Essen, Bochum, Hagen, and Hamm - shows intense demand, with onboard volumes consistently at 372 to 373 passengers, reflecting sustained over-capacity conditions along these heavily urbanized and interconnected sections. The corridor reaches a broad and extended demand peak between Göttingen and Leipzig, where passenger loads remain near the maximum modeled capacity for an extended portion of the journey.

Following Leipzig, a gradual decline begins toward the east. Between Dresden and Wrocław, onboard numbers fall to 348 passengers, and decrease further to 255 passengers on the final Wrocław–Warsaw leg. This pattern reflects the transition from Germany's dense polycentric regions to the more linear demand landscape characteristic of western and central Poland.

The cost structure mirrors these spatial dynamics. Most western and central legs exhibit moderate per-leg costs, typically ranging between €500 and €3,500, but costs rise considerably in the eastern section - especially between Dresden, Wrocław, and Warsaw - where long inter-city distances

sharply increase per-leg expenditure, reaching values of €7,801 and €6,343. The border indicator identifies two international transitions, namely between Arnhem and Duisburg and again between Dresden and Wrocław, highlighting the route's transnational character and the operational complexities tied to varying infrastructure charges and national regulatory systems.

The distribution of boarding and alighting activity confirms the route's asymmetric demand profile. Amsterdam initiates the journey with 259 boardings and generates €36,615 in revenue, establishing its role as the dominant western origin. Utrecht and Arnhem add substantial inflows of 120 and 9 passengers respectively, reinforcing the early buildup of demand. The Ruhrgebiet - from Duisburg through Hagen - features a dense pattern of boardings distributed across multiple stations, accompanied by moderate alighting activity that reflects the region's high-frequency regional mobility embedded within this international service. Further east, Leipzig contributes 70 new boardings and Dresden adds another 65, making both cities major turnover points where high alighting levels coincide with renewed inflows. Beyond Wrocław, demand becomes increasingly destination-oriented, with relatively few new passengers joining the train and a clear focus on end-of-line travel. This culminates in Warsaw, where all remaining 255 passengers fully alight, marking a complete turnover at the eastern terminus.

Among the entire benchmark set, the Amsterdam–Warsaw corridor is unique for combining a very long spatial reach with strongly clustered demand peaks along its western and central sections. It illustrates the complexities of operating trans-European services across regions with sharply differing population densities, varying rail market maturity, and contrasting infrastructure characteristics. From a line-planning perspective, the corridor highlights a number of key challenges and opportunities. The substantial capacity shortages observed in Germany demonstrate the need for larger rolling stock or increased service frequency. At the same time, the corridor's strong profitability despite high rejection levels suggests that unmet demand is considerable and could be captured with appropriate service adjustments. The sharp shifts in load intensity between western and eastern segments underscore the importance of adaptive planning mechanisms for multi-country routes, while the sheer length and international complexity of the corridor make it an ideal test case for integrated European network strategies.

As the final benchmark example, the Amsterdam–Warsaw line expands the geographic and operational scope of the analysis, connecting Western Europe's established rail markets with the rapidly developing long-distance segments of Central and Eastern Europe. It thereby provides a crucial reference point for evaluating service planning, capacity allocation, and cross-border integration across the broader Central European rail network, linking the insights gained from national and regional corridors into a cohesive, continent-spanning framework.

In summary, the seven benchmark routes presented above collectively capture the structural and spatial diversity of the Central European railway network. They encompass both domestic high-speed connections and long-distance international corridors, linking Western, Central, and parts of Eastern Europe through a variety of network configurations and demand characteristics. Each route provides a distinct operational and geographical context, allowing for a comprehensive assessment of different service types - from mature high-speed systems to complex transnational lines.

These benchmark routes form the empirical foundation for the subsequent analysis within this thesis. In the following sections, they will serve as reference cases against which the results generated by the line planning solver are evaluated and compared. By contrasting the solver's optimized line plans with these real-world examples, it becomes possible to assess both the model's

validity and its capacity to capture the economic and operational dynamics of Central Europe's interconnected rail system.

6.2 Results for Single Objective LPP

The formulation of objective functions represents a central step in the line planning problem. In order to maintain clarity and ensure traceability of the results, the analysis begins with simple, single-objective formulations. These baseline models minimize either the total travel distance or the total travel time and thus provide lower bounds and benchmarks against which more complex models can later be compared. Starting with these simplified formulations has two main advantages: first, it allows for a direct interpretation of the model behavior without confounding trade-offs, and second, it establishes reference solutions that serve as anchors for subsequent analyses.

Once the baseline objectives are established, the model is gradually extended by incorporating additional dimensions such as revenue generation and operational cost. Since railway planning naturally involves conflicting goals - for example, maximizing revenue while minimizing travel time and distance - a single-objective formulation cannot fully capture the complexity of the problem. For this reason, the multi-objective problem is addressed through a Pareto-based method, which allows trade-offs between competing objectives to be explicitly quantified. This approach provides decision makers with a spectrum of efficient solutions, each representing a different balance between performance indicators.

By structuring the analysis in this incremental way - from simple single-objective formulations to multi-objective Pareto frontiers - the thesis not only ensures methodological transparency but also underlines the practical relevance of the optimization results. The following sections therefore begin with the two baseline objectives of minimizing distance and minimizing travel time, before moving on to more advanced formulations.

Following the implementation of the Line Planning Solver, the next step involves accessing and evaluating the fundamental information of the seven benchmark routes. These benchmark routes serve as representative reference lines within the Central European rail network, reflecting different spatial and operational characteristics under the defined optimization objectives. By examining their structural and performance attributes - such as route composition, total distance, travel time, stop distribution, and revenue potential - the benchmark analysis provides essential insights into how the model translates theoretical constraints and objectives into practical route configurations. This step establishes the analytical foundation for comparing network performance across optimization criteria and supports a deeper understanding of efficiency patterns, spatial coverage, and economic viability within the modeled transport system.

To ensure the model's validity and comparability, the optimization framework was calibrated using a predefined set of seven benchmark routes that represent the structural diversity of the target rail network. These benchmark routes capture a broad operational spectrum, ranging from short-distance connections with eight intermediate stops to long-haul services comprising up to sixteen stops. The corresponding travel characteristics span from a minimum travel time of 358 minutes to a maximum of 1,074 minutes, while total route distances vary between 1228.1 km and 2,371.7 km. These reference parameters define the operational envelope within which the optimization model must operate. In the graphical user interface of the Line Planning Solver, these conditions are mirrored through specific input values: a fleet size of seven trains, an enforced number of seven routes (minimum and maximum set to seven to achieve an exact match), stop limits between eight and sixteen, and a maximum allowable travel time of 1,100 minutes.

The optimization objective is configured as “Minimization of total travel time”, with a maximum of one train per route, ensuring a direct correspondence between model output and benchmark network structure. This configuration enables the solver to generate a comparable route network that aligns with the empirical properties of the benchmark system, thereby facilitating subsequent validation and performance analysis.

6.3 Results for LPP Minimizing Travel Time

The first baseline objective minimizes total travel time, reflecting passenger-oriented service quality and network efficiency. While distance is closely linked to infrastructure usage and operating costs, travel time more directly captures perceived attractiveness, competitiveness against alternative modes, and the potential for increased vehicle rotation. Consequently, minimizing travel time constitutes a natural reference objective for evaluating the temporal performance of alternative line planning solutions.

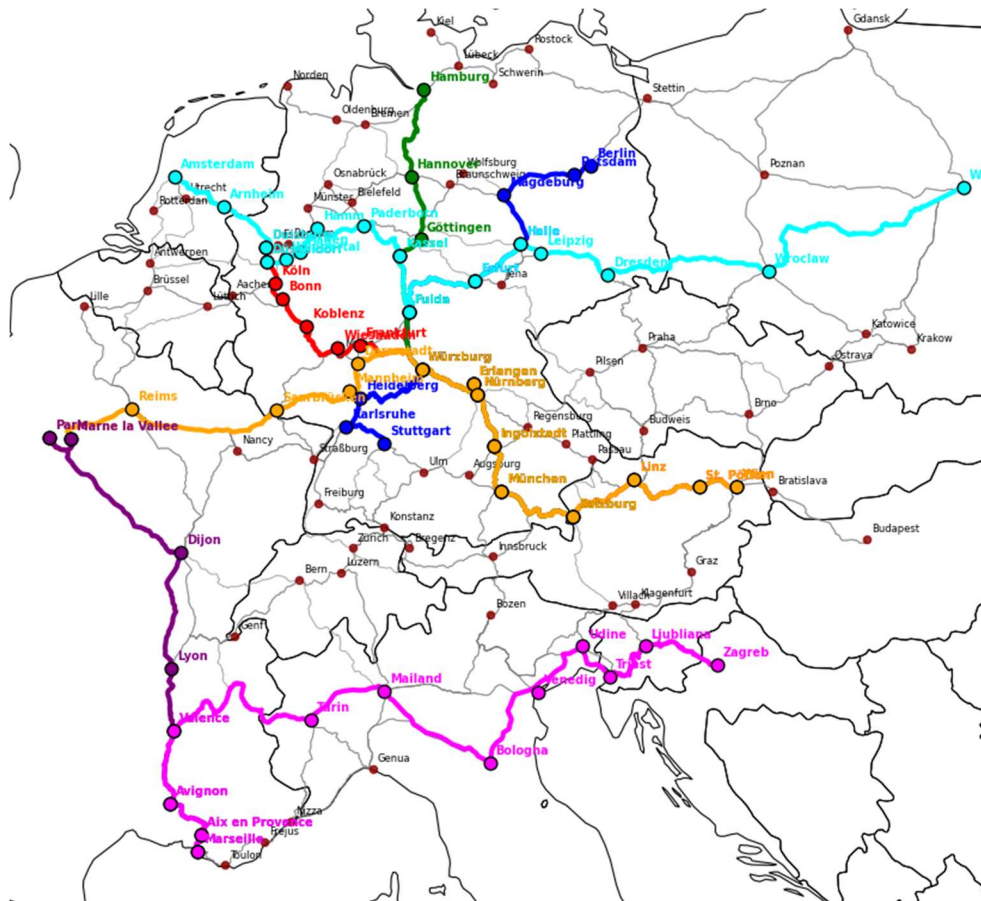


Figure 14: Solution minimization travel time

Bench mark Route	Direction (Origin → Destination)	Time (min)	Distance (km)	Revenue (€)	Total Cost (€)	Profit (€)	Profit Mar- gin (%)	Total Passen- gers car- ried
1	Vienna → St.Pölten → Linz → Salzburg → München → Ingolstadt → Nuremberg → Erlangen → Würzburg → Frankfurt → Wiesbaden → Koblenz → Bonn → Cologne → Düsseldorf → Duisburg	459 (-0.2%)	1769 (+10.3%)	62751.0 (+1.2%)	24236 (-0.2%)	38515 (+3.5%)	61.4 (+2.3%)	778.0 (+4.1%)
2	Berlin → Potsdam → Magdeburg → Halle → Erfurt → Fulda → Würzburg → Heidelberg → Karlsruhe → Stuttgart	423.0 (-10.8%)	695.2 (-43.3%)	47500.0 (-10.3%)	13621.0 (-41.5%)	33878.0 (+14.1%)	71.3 (+27.3%)	647.0 (-0.11%)
3	Hamburg → Hannover → Göttingen → Kassel → Fulda → Würzburg → Erlangen → Nuremberg → Ingolstadt → Munich → Salzburg	358 (0.0%)	1398.7 (0.0%)	50139.0 (0.0%)	26388 (0.0%)	23751 (0.0%)	47.4 (0.0%)	661.0 (0.0%)
4	Paris → Marne la Vallee → Reims → Saarbrücken → Mannheim → Darmstadt → Würzburg → Erlangen → Nuremberg → Ingolstadt → Munich → Salzburg → Linz → St. Pölten → Vienna	543 (-12.1%)	2277.8 (+10.3%)	90114 (+5,9%)	32998 (+22.5%)	57116 (-1.7%)	63.4 (-7.1%)	862.0 (+9.1%)
5	Paris → Marne la Vallee → Dijon → Lyon → Valence → Avignon → Aix en Provence → Marseille	369 (0.0%)	1315.1 (0.0%)	41798.0 (0.0%)	16906 (0.0%)	24892 (0.0%)	59.6 (0.0%)	486.0 (0.0%)
6	Marseille → Aix en Provence → Avignon → Valence → Turin → Milan → Bologna → Venice → Udine → Triest → Ljubliana → Zagreb	949.0 (-11.6%)	2382.8 (+28.7%)	58308.0 (+18.6%)	14740.0 (-27.2%)	43567.0 (+50.7%)	74.7 (+27.0%)	769.0 (+11.9%)
7	Amsterdam → Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn → Kassel → Fulda → Erfurt → Halle → Leipzig → Dresden → Wroclaw → Warszawa	878.0 (-8.9%)	2471.3 (+4.1%)	90125.0 (-2.6%)	37189.0 (-0.1%)	52936.0 (-4.2%)	58.7 (-1.8%)	782.0 (+3.8%)

Table 10: Solution table for minimization of travel time

Compared to the benchmark routes, the resulting solution exhibits a clear structural shift toward more direct alignments and reduced detours, particularly along the east–west and north–south corridors (Figure 14). For instance, Benchmark Route 1 (Vienna–Duisburg) is restructured via Salzburg, Munich, and Ingolstadt, yielding a slightly shorter travel time (459 minutes versus 460 minutes) while simultaneously increasing passenger volumes and profit (Table 10). Similarly, the

Berlin–Stuttgart corridor (Benchmark Route 2) is shortened both in time and distance, with intermediate stops concentrated on high-demand nodes such as Würzburg and Heidelberg. Across the network, none of the activated routes exceeds eight intermediate stops, a direct consequence of the objective’s penalization of additional dwell times and deviations.

From an economic perspective, the time-optimal solution remains system-wide profitable, generating total revenues of approximately €440,735 against operating costs of €166,078, resulting in an aggregate profit of about €274,657 (Table 10). Relative to the benchmark configuration, profitability is more evenly distributed across routes, with particularly strong performance observed on dense, high-demand corridors such as Vienna–Duisburg, Berlin–Stuttgart, and Marseille–Zagreb. At the same time, long-distance international services - especially those connecting Southern and Central Europe - remain viable despite their extended distances, indicating that travel-time efficiency partially offsets higher operating costs. This contrasts with the benchmark system, where profitability relied more strongly on a small subset of high-performing routes, implying a higher degree of cross-subsidization.

Passenger loads further underline the effectiveness of the optimized solution. Peak segment loads range between approximately 486 and 862 passengers, consistently exceeding or matching those observed in the benchmark routes. This confirms that the solver’s time-oriented selection not only improves temporal efficiency but also aligns well with spatial demand patterns. Overall, the optimized network represents a more compact, time-efficient evolution of the benchmark system, preserving its core corridors while reducing unnecessary detours and reinforcing high-demand axes. The results demonstrate that substantial improvements in travel time can be achieved without sacrificing economic viability, thereby establishing a robust baseline for subsequent profit-based and multi-objective analyses.

6.4 Results for the LPP Minimizing Distance

The second baseline formulation minimizes the total travel distance (Figure 15) across all selected arcs in the network. Distance constitutes a robust proxy for operational effort and resource consumption, as shorter routes generally imply lower traction energy use, reduced rolling-stock wear, fewer maintenance requirements, and lower infrastructure access charges. In contrast to travel-time minimization, which reflects passenger-perceived service quality, distance minimization provides a structurally grounded measure of spatial efficiency that is largely independent of timetable design or demand distribution.

When applying this objective function, the Line Planning Solver identifies exactly the same seven routes as defined in the benchmark configuration (Table 11), with no deviations in route structure, ordering of stations, or network composition. Consequently, all key performance indicators - travel time, distance, revenue, operating cost, profit, profit margin, and passenger loads - remain identical to those of the benchmark system. This outcome indicates that the benchmark routes are already globally distance-efficient within the feasible solution space defined by the model constraints. In other words, no alternative combination of routes exists that can reduce total network distance without violating feasibility conditions such as maximum travel time, stop constraints, or fleet size limitations.

Rather than representing a limitation, this result serves as a strong internal consistency and robustness check for the modeling framework. The solver's ability to reproduce the benchmark network under an independent optimization criterion confirms that the benchmark solution lies on a structural optimum with respect to spatial efficiency. This finding validates both the correctness of the distance-based objective formulation and the stability of the solution space. Having estab-

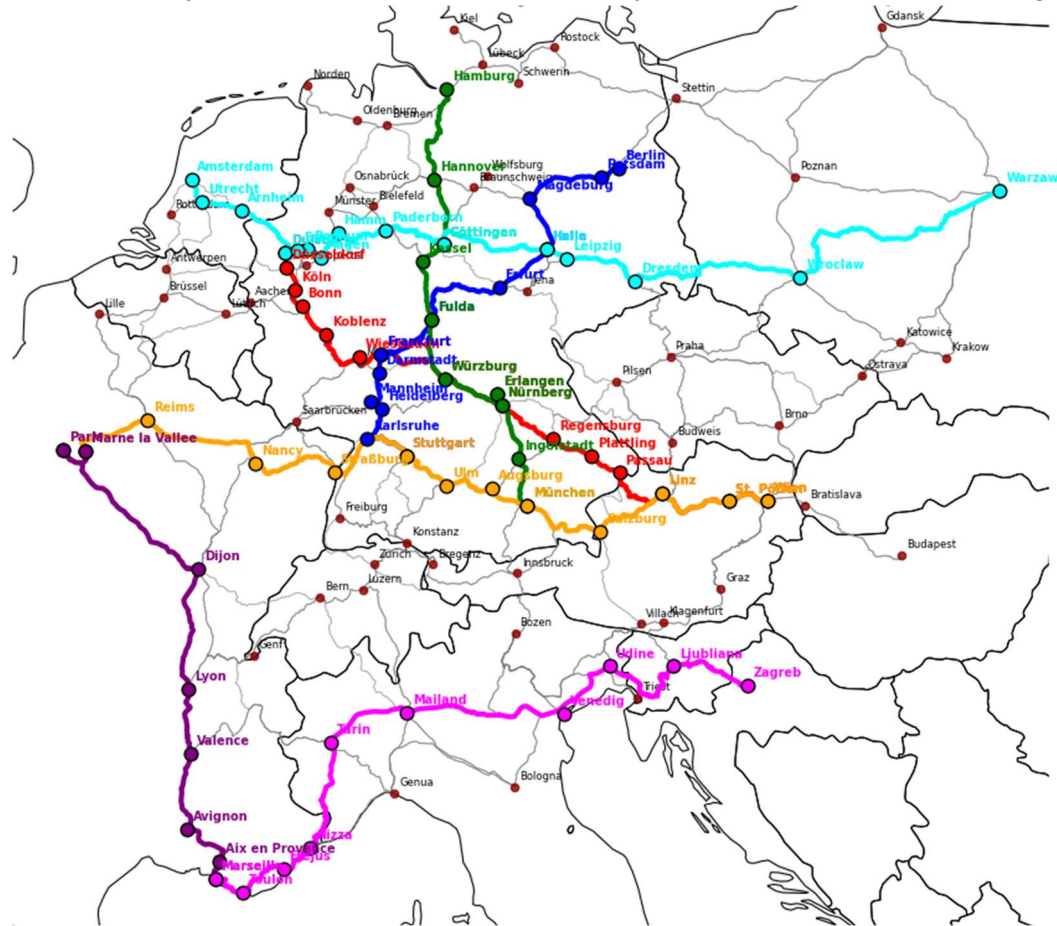


Figure 15: Solution minimization travel distance

lished that the benchmark network is already distance-optimal, the analysis can now proceed with confidence to the profit-maximization scenario, which introduces economically meaningful trade-offs between demand, revenue generation, and operational costs.

Bench mark Route	Direction (Origin → Destination)	Time (min)	Distance (km)	Revenue (€)	Total Cost (€)	Profit (€)	Profit Margin (%)	Max Pas- sengers On Board
1	Vienna → St. Pölten → Linz → Passau → Plattling → Regensburg → Nuremberg → Erlangen → Würzburg → Frankfurt → Wiesbaden → Koblenz → Bonn → Cologne → Düsseldorf → Duisburg	460 (0.0%)	1603 (0.0%)	61945.0 (0.0%)	24751 (0.0%)	37194 (0.0%)	60.0 (0.0%)	747.0 (0.0%)
2	Berlin → Potsdam → Magdeburg → Halle → Erfurt → Fulda → Frankfurt → Darmstadt → Mannheim → Heidelberg → Karlsruhe → Stuttgart	478 (0.0%)	1228.1 (0.0%)	52994.0 (0.0%)	23320 (0.0%)	29674 (0.0%)	56.0 (0.0%)	733.0 (0.0%)
3	Hamburg → Hannover → Göttin- gen	358 (0.0%)	1398.7 (0.0%)	50139.0 (0.0%)	26388 (0.0%)	23751 (0.0%)	47.4 (0.0%)	661.0 (0.0%)

Bench mark Route	Direction (Origin → Destination)	Time (min)	Distance (km)	Revenue (€)	Total Cost (€)	Profit (€)	Profit Margin (%)	Max Pas- sengers On Board
	→ Kassel → Fulda → Würzburg → Nuremberg → In- golstadt → Munich → Salzburg							
4	Paris → Marne-la-Vallée → Reims → Nancy → Strasbourg → Stuttgart → Ulm → Munich → Salzburg → Linz → St. Pölten → Vienna	618 (0.0%)	2064.1,4 (0.0%)	85081.0 (0.0%)	26937 (0.0%)	58144 (0.0%)	68.3 (0.0%)	790.0 (0.0%)
5	Paris → Marne-la-Vallée → Dijon → Lyon → Valence → Avignon → Aix-en-Provence → Marseille	369 (0.0%)	1315.1 (0.0%)	41798.0 (0.0%)	16906 (0.0%)	24892 (0.0%)	59.6 (0.0%)	486.0 (0.0%)
6	Marseille → Toulon → Fréjus → Nice → Turin → Milan → Venice → Ljubljana → Zagreb	1074.0 (0.0%)	1850.6 (0.0%)	49161.0 (0.0%)	20262 (0.0%)	28899 (0.0%)	58.8 (0.0%)	687.0 (0.0%)
7	Amsterdam → Utrecht → Arnhem → Duisburg → Essen → Bochum → Leipzig → Dresden → Wrocław → Warsaw	964.0 (0.0%)	2371.7 (0.0%)	92553.0 (0.0%)	37245 (0.0%)	55308 (0.0%)	59.8 (0.0%)	753.0 (0.0%)

Table 11: Solution table for minimization of travel distance

6.5 Results for LPP Maximizing Profit

The third optimization scenario focuses on the maximization of total system profit, representing the objective most closely aligned with real-world railway operator decision-making. Unlike the travel-time and travel-distance baselines, which primarily serve as robustness checks, profit maximization explicitly balances revenue generation, passenger demand, and operating costs, thereby internalizing the key economic trade-offs inherent in commercial rail service planning.

Under this objective, the Line Planning Solver identifies a set of seven routes that differs structurally from the benchmark configuration (Figure 156) while still preserving its core international corridors. Compared to the benchmark routes, several connections are extended or restructured to include additional high-demand intermediate nodes, such as Bremen on the Hamburg–Salzburg axis and Frankfurt on the Paris–Wien corridor. These modifications increase passenger capture and revenue potential at the expense of moderately longer travel times and distances. For instance, the Hamburg–Salzburg route expands from 1398.7 km in the benchmark to 1596 km, accompanied by a revenue increase of more than €6,725, while maintaining a solid profit margin of nearly 47%. Similarly, the Paris–Vienna corridor is lengthened relative to the benchmark but achieves a similar absolute profit (€57,116 versus €58,144), driven by substantially increased passenger volumes (Table 12).

From a system-wide perspective, the profit-maximizing network significantly outperforms the benchmark configuration in economic terms. Total revenues increase markedly, most notably on the Amsterdam–Warszawa and Paris–Vienna corridors, which generate profits exceeding €100,000 and €90,000, respectively. Profit margins remain consistently high across all routes, ranging between approximately 47% and 65%, indicating that the solver successfully avoids low-performing services that would require cross-subsidization. In contrast to the benchmark system

- where profitability is already strong but partially driven by structurally efficient routes - the profit-maximizing solution actively reshapes route geometry to amplify demand concentration and revenue density.

Passenger load patterns further confirm this shift in optimization logic. Maximum onboard passenger volumes increase on nearly all long-distance routes compared to the benchmark, with peak values reaching up to 862 passengers on the Paris–Vienna connection. This reflects the

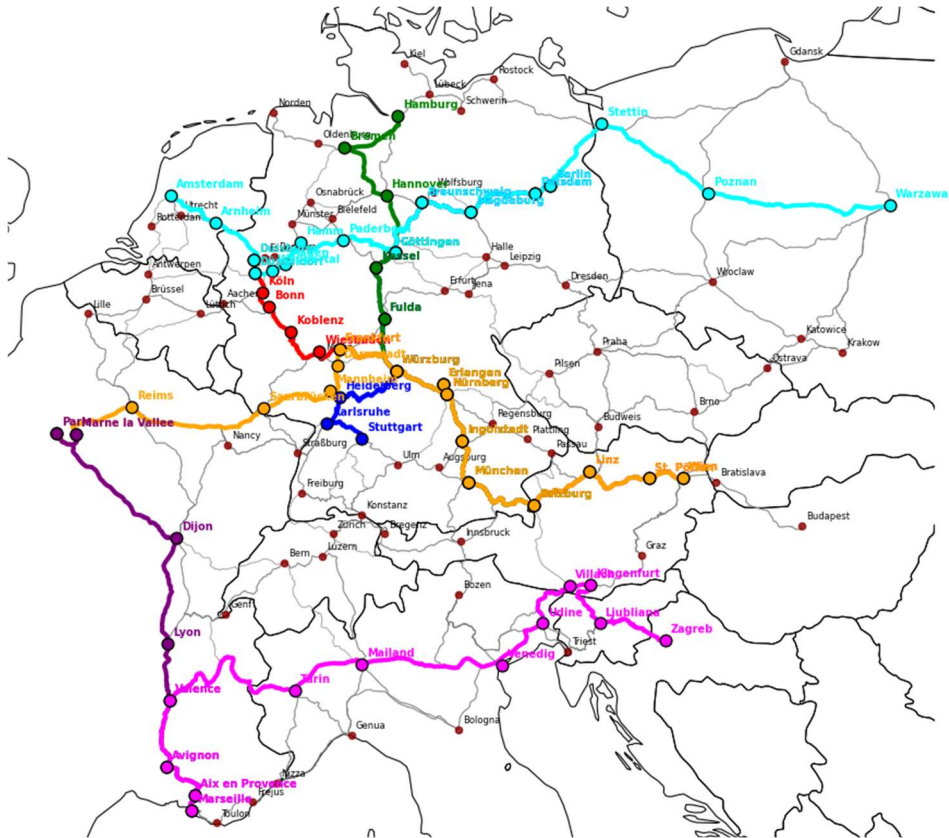


Figure 16: Solution maximization profit

solver’s tendency to favor routes that traverse large metropolitan areas and high-demand corridors, even if this entails additional intermediate stops or slightly longer alignments. Importantly, all selected routes remain profitable, demonstrating that increased spatial coverage and passenger aggregation do not compromise cost efficiency.

Overall, the profit-maximizing solution represents a deliberate departure from the benchmark system’s emphasis on structural or temporal efficiency toward a demand-driven, revenue-oriented network design. While travel times and distances increase on several routes relative to the benchmark, these changes are economically justified by higher passenger volumes and substantially improved financial performance. This comparison highlights the fundamental trade-off between operational efficiency and commercial viability and illustrates how the Line Planning Solver adapts route structures when explicitly aligned with operator-centric objectives.

Bench Route	Direction (Origin → Destination)	Time (min)	Distance (km)	Revenue (€)	Total Cost (€)	Profit (€)	Profit Margin (%)	Max Passengers On Board
1	Vienna → St.Pölten → Linz → Salzburg → Munich → Ingolstadt → Nürnberg → Erlangen → Würzburg → Frankfurt → Wiesbaden → Koblenz →	459 (-0.2%)	1769 (+10.3%)	62751.0 (+1.2%)	24236 (-0.2%)	38515 (+3.5%)	61.4 (+2.3%)	778.0 (+4.1%)

Bench mark Route	Direction (Origin → Desti- nation)	Time (min)	Distance (km)	Revenue (€)	Total Cost (€)	Profit (€)	Profit Mar- gin (%)	Max Pas- sengers On Board
	Bonn → Köln → Düssel- dorf → Duisburg							
2	Berlin → Potsdam → Mag- deburg → Braunschweig → Göttingen → Kassel → Fulda → Würzburg → Hei- delberg → Karlsruhe → Stuttgart	496 (+3.7%)	1328.7 (+8.1%)	53994.0 (+1.8%)	25621.0 (+9.8%)	28373.0 (-4.3%)	52.5 (-6.2%)	756.0 (+3.1%)
3	Hamburg → Bremen → Hannover → Göttingen → Kassel → Fulda → Würz- burg → Erlangen → Nu- remberg → Ingolstadt → Munich → Salzburg	416 (+16.2%)	1596 (+14.1%)	56864 (+13.4%)	30113 (+14.1%)	26751 (+13.7%)	47.0 (-0.8%)	731.0 (+10.5%)
4	Paris → Marne la Vallee → Reims → Saarbrücken → Mannheim → Darmstadt → Frankfurt → Würz- burg → Erlangen → Nu- remberg → Ingolstadt → Munich → Salzburg → Linz → St. Pölten → Vi- enna	543.0 (-12.1%)	2277.8 (+10.3%)	90114.0 (+5.9%)	32998 (+22.5%)	57116 (-1.7%)	63.4 (-7.1%)	862.0 (+9.1%)
5	Paris → Marne la Vallee → Dijon → Lyon → Valence → Avignon → Aix en Pro- vence → Marseille	369 (0.0%)	1315.1 (0.0%)	41798.0 (0.0%)	16906 (0.0%)	24892 (0.0%)	59.6 (0.0%)	486.0 (0.0%)
6	Marseille → Aix en Pro- vence → Avignon → Va- lence → Turin → Milan → Venice → Udine → Vil- lach → Klagenfurt → Ljubiana → Zagreb	951.0 (-11.4%)	2188.6 (+18.2%)	60455.0 (+22.9%)	20483.0 (+1.0%)	39972.0 (+38.3%)	65.7 (+11.7%)	777.0 (+13.1%)
7	Amsterdam → Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn → Göttingen → Braun- schweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan → Warszawa	879.0 (-8.8%)	2469.4 (+4.1%)	101827.0 (+10.0%)	37170.0 (-0.2%)	64657 (+16.9%)	63.5 (+6.18%)	755.0 (+0.2%)

Table 12: Solution table for maximization of profit

6.6 Results for Multi-objective LPP

To derive a more realistic and operationally meaningful network configuration, the optimization framework was extended from a single-objective to a multi-objective formulation. In this enhanced solver, profit, travel time, and travel distance act as jointly weighted indicators, allowing the user to balance economic efficiency with service quality and infrastructural efficiency. This represents a necessary methodological shift, as real-world line planning must account for both financial viability and passenger-oriented performance metrics. The solver was therefore upgraded to include an interactive weighting interface, enabling manual input of relative importance factors for each objective dimension. For the analysis presented in the following section, the weights were set to

0.45 for profit, 0.35 for travel time, and 0.2 for distance, reflecting a configuration in which economic considerations remain dominant but operational efficiency exerts significant influence. This multi-criteria setup provides a more nuanced and realistic basis for evaluating candidate routes and assessing the trade-offs inherent in practical railway network design.

Using the weighted multi-objective formulation - where profit, travel time, and travel distance are combined into a single weighted performance metric - the solver activates seven long-distance routes that jointly generate total revenue of €349,071, operating costs of €242,203, and an aggregate profit of €106,868. This corresponds to an average profit margin of approximately 30.6%, with individual routes ranging from about 25.6% to 33.5%. The selected services form two dominant corridor families: (i) Southern France–Benelux–Rhine/Ruhr connections (e.g., Fréjus/Nice → Essen/Duisburg, Osnabrück → Toulon) and (ii) Northwestern Europe–Poland axes (Utrecht/Arnheim/Amsterdam → Warsaw). These patterns illustrate that the multi-objective weighting favors routes with both strong international demand flows and acceptable operational efficiency (Table 13).

Route ID	Main Relation (shortened)	Time (min)	Distance (km)	Revenue (€)	Costs (€)	Profit (€)	Profit Margin*
7174	Fréjus → Essen	747	2,372	47,905	32,134	15,771	~32.9%
28842	Osnabrück → Toulon	781	2,376	44,690	33,250	11,440	~25.6%
31654	Utrecht → Warsaw	859	2,407	53,098	36,553	16,545	~31.1%
34837	Arnheim → Warsaw	829	2,296	52,007	35,310	16,697	~32.1%
41270	Nice → Duisburg	773	2,433	45,880	32,733	13,147	~28.7%
44705	Amsterdam → Warsaw	879	2,469	52,790	37,170	15,620	~29.6%
54094	Arnheim → Warsaw (variant)	834	2,281	52,702	35,055	17,647	~33.5%
Total	–	–	–	349,071	242,203	106,868	~30.6% average

Table 13: Solution table for pareto optimum fixed weights

Travel times range from 747 to 879 minutes, while distances lie between 2,281 and 2,469 km. Compared to the pure profit-maximizing outcome, the multi-objective solution shows a tendency toward slightly shorter and more operationally balanced rotations. Notably, Route 54094 (Arnheim → Warsaw) achieves the shortest distance (2,281 km) while simultaneously delivering the highest profit (€17,647) and the highest profit margin (~33.5%). In contrast, Route 28842 (Osnabrück → Toulon), despite considerable demand, exhibits a less favorable revenue-cost ratio (profit margin ~25.6%), which demonstrates how the weighting of travel time and distance modulates the route selection: the solver may prefer operationally efficient lines even if they are not the highest-grossing ones.

Overall, the weighted-sum approach yields a portfolio of routes that are economically attractive but also geographically diverse and operationally moderate, representing a more realistic compromise between financial objectives and service quality considerations than the single-objective profit-maximization model.

From a geographical perspective, the multi-objective solution still exhibits a strong concentration on two dominant international corridors: (i) a south–north axis linking the Mediterranean coast (Nice/Fréjus/Toulon/Marseille/Aix-en-Provence/Avignon/Valence/Lyon) with Belgium and the Rhine-Ruhr area (Brussels/Liège/Aachen/Cologne/Düsseldorf/Duisburg/Essen), and (ii) a west–east axis connecting the Dutch/German border region (Amsterdam/Utrecht/Arnheim, plus Rhine-

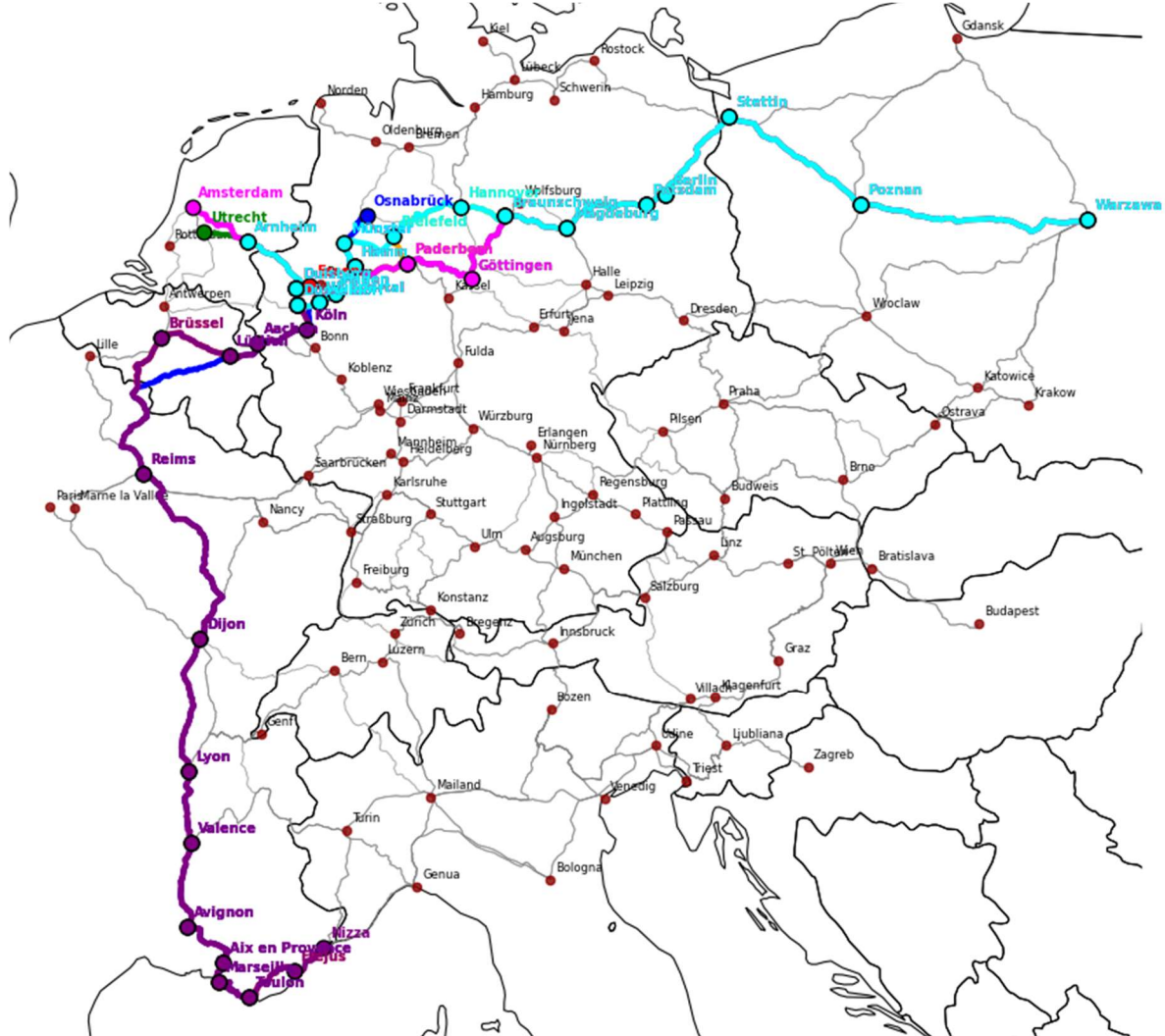


Figure 17: Solution Pareto optimum

Ruhr and central German cities) with Poland and its capital Warsaw (Figure 17). These patterns are almost identical to those obtained under pure profit maximization, both in terms of origin-destination structure and in the dominance of long international links with strong demand. The fact that the introduction of weighted travel time and distance (with weights 0.35 and 0.2, respectively, versus 0.45 for profit) barely changes the spatial composition of the optimal line portfolio indicates that the chosen weighting scheme is not sufficiently influential to shift the solution away from primarily profit-driven routes. In other words, the economic gradients are so pronounced that the current weights do not create a meaningful trade-off in the objective space; the solver still “sees” nearly the same routes as optimal. To obtain a more nuanced and robust understanding of the trade-offs between profit, travel time, and distance, the next step is therefore to create a multi-objective solution space including multiple trade-off points on Pareto front, in which the weights of the three criteria are systematically randomized across multiple runs, allowing the exploration of the full Pareto frontier and the identification of genuinely alternative, more service-oriented network configurations.

As the final step toward obtaining a robust and realistic line planning solution, the computational framework was significantly enhanced to allow for a comprehensive multi-Pareto analysis. The previous experiments demonstrated that the weighted-sum approach - despite balancing profit, travel time, and distance - still reproduced almost identical route portfolios to the pure profit-maximization model. This indicated that the original weight settings were not sufficiently influential to meaningfully shift the solution space. To overcome this limitation and to fully map the trade-offs between the three conflicting objectives, two major methodological extensions were implemented.

First, the number of K-shortest paths per OD pair was increased from $K = 8$ to $K = 20$, resulting in a substantially larger and more diverse route pool of 200,097 feasible line candidates (≤ 1100 min), thereby expanding the solution space accessible to the optimizer. Second, the number of randomly sampled weight combinations per multi-objective run was raised to 20, providing a significantly richer sampling of the objective space. Each sample assigns a different triplet of weights to travel time, distance, and profit within the weighted-sum model. This setup enables the solver to explore the entire Pareto frontier rather than converging prematurely to a profit-dominated solution. The following table 14 summarizes all 20 weight configurations used in the multi-run Pareto sampling process.

Iteration	w_time	w_dist	w_profit
1	0.429	0.457	0.114
2	0.411	0.179	0.410
3	0.345	0.564	0.091
4	0.057	0.572	0.371
5	0.050	0.412	0.538
6	0.317	0.295	0.388
7	0.108	0.090	0.803
8	0.331	0.530	0.140
9	0.540	0.179	0.281
10	0.326	0.416	0.259
11	0.138	0.391	0.472
12	0.353	0.268	0.379
13	0.480	0.141	0.379
14	0.265	0.487	0.248
15	0.171	0.232	0.597
16	0.553	0.288	0.160
17	0.054	0.530	0.416
18	0.324	0.367	0.309
19	0.436	0.092	0.471
20	0.241	0.343	0.416

Table 14: Random generated pareto optimum weights

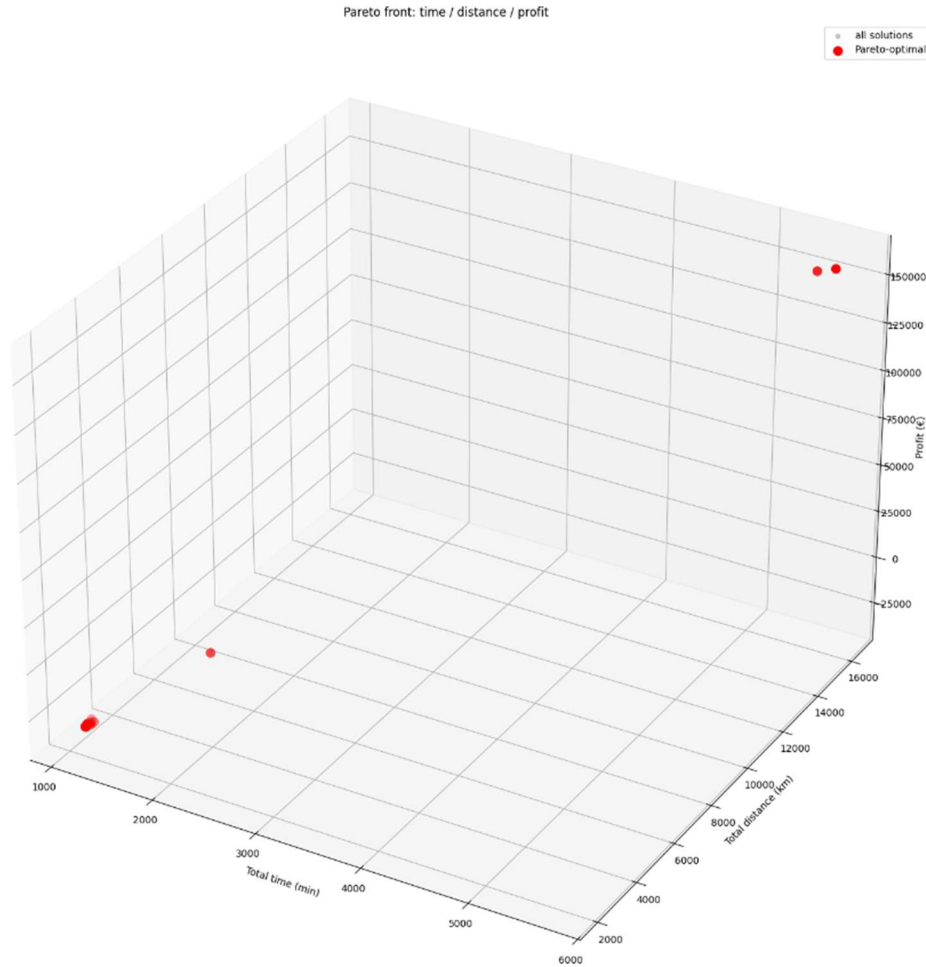


Figure 18: Illustration of Pareto Optimum

The figure 18 illustrates the resulting Pareto front obtained from the multi-objective sampling across 20 randomized weight combinations. Displayed in a three-dimensional space, the axes represent the total travel time of the selected route portfolio (x-axis), the total travel distance of all activated routes (y-axis), and the total system profit (z-axis). Each red point corresponds to a non-dominated solution, meaning that no other sampled solution simultaneously improves all three criteria.

The three visible red points show clear trade-offs between operational efficiency and profitability. One solution lies toward the lower end of the total travel time axis, indicating a comparatively fast system configuration, but this comes with a slightly reduced profit. Another solution sits at the higher end of the profit axis, representing the most profitable portfolio, yet it requires longer total travel time and a higher accumulated distance. The intermediate point shows a balanced compromise between both extremes.

Overall, the figure demonstrates that no single solution dominates the others across all objectives. Instead, the Pareto front reveals structurally different optimal trade-off configurations:

- a time-efficient but less profitable network,
- a profit-maximizing network with longer operational characteristics, and
- a balanced compromise solution between the two.

This visualization validates the role of the multi-Pareto approach: it exposes trade-off structures that the weighted-sum method alone could not uncover, enabling a more nuanced selection of the final strategic rail network.

The following table 15 consolidates all unique railway routes that emerged across the 20 Pareto-optimal solutions generated in the multi-objective optimization process. Although each Pareto solution activates seven routes, the high degree of overlap between solutions results in only eight truly unique routes being represented in the final set. These routes form the fundamental structural components of the Pareto frontier and together describe the operational patterns that repeatedly proved optimal under varying weight combinations for travel time, distance and profit. By isolating these eight distinct routes, the analysis can focus on the core network configurations that consistently drive optimal trade-offs across the full spectrum of objective priorities.

Route ID	Route Description
24002	Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn → Bielefeld → Hannover → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan → Warszawa
71684	Utrecht → Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn → Göttingen → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan → Warszawa
80704	Amsterdam → Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn → Göttingen → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan → Warszawa
104877	Frejus → Toulon → Marseille → Aix en Provence → Avignon → Valence → Lyon → Dijon → Reims → Brüssel → Lüttich → Aachen → Köln → Düsseldorf → Duisburg → Essen
110145	Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Münster → Osnabrück → Hannover → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan → Warszawa
113158	Frejus → Toulon → Marseille → Aix en Provence → Avignon → Valence → Lyon → Dijon → Reims → Brüssel → Lüttich → Aachen → Köln → Düsseldorf → Wuppertal → Essen
137534	Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Münster → Bielefeld → Hannover → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan → Warszawa
198025	Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Münster → Osnabrück → Bielefeld → Hannover → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan → Warszawa

Table 15: Solution routes pareto optimum random weights

An examination of the eight unique routes reveals a strong internal pattern within the Pareto frontier: the majority of routes follow a north–south European axis, connecting the Dutch and German urban clusters with the major eastern corridor toward Poznan and Warszawa. Routes 24002, 71684, 80704, 110145, 137534, and 198025 all share the characteristic structure of passing through the dense Rhine–Ruhr conurbation and subsequently linking into the long eastbound high-demand corridor toward Poland. These recurring route geometries indicate that the solver consistently identifies this corridor as the most profitable and operationally balanced backbone,

regardless of changes in objective weighting. In contrast, routes 104877 and 113158 represent the southern Mediterranean-to-northwest axis, connecting French coastal regions with Belgium and western Germany. Their presence in the Pareto frontier suggests an important complementary demand structure linking touristic and densely populated regions across France and the Benelux area. The coexistence of these two major corridor families -central/eastern and southern/northwestern - demonstrates that the optimization process repeatedly converges on a limited number of structurally robust route archetypes. This, in turn, underscores that despite weight variation, the underlying passenger demand distribution strongly guides the formation of Pareto-optimal solutions.

To evaluate the practical relevance of the Pareto-optimal solutions, the next step involves a systematic comparison with the predefined benchmark routes. Although none of the generated Pareto solutions achieves complete coverage of all benchmark relations simultaneously, several individual routes exhibit partial or substantial alignment with specific benchmark corridors. Consequently, we assess each benchmark route independently by identifying the most suitable matching candidate within the Pareto set. In cases where no Pareto-route sufficiently reflects the benchmark structure, we complement the analysis through a manual computation using the OD-solver. This OD-solver allows the manual specification of origin and destination pairs and computes the optimal route between them based on randomized weight vectors, ensuring methodological consistency with the broader multi-objective framework. Through this combined approach - benchmark matching and targeted OD-based reconstruction - we establish a comprehensive evaluation of how well the optimized network reflects real-world strategic planning objectives.

Benchmark Route #	Benchmark City Route	Comparing Solution Route	Origin of Solution Route
1	Vienna → St. Pölten → Linz → Passau → Regensburg → Nuremberg → Würzburg → Frankfurt → Cologne → Düsseldorf → Duisburg	Vienna → St. Pölten → Linz → Passau/ Salzburg → Plattling/ Munich → Regensburg/ Ingolstadt → Nuremberg → Erlangen → Würzburg → Frankfurt → Wiesbaden → Koblenz → Bonn → Cologne → Düsseldorf → Duisburg	Route 1 & 2 OD Pareto Solver
2	Berlin → Potsdam → Magdeburg → Halle → Erfurt → Fulda → Frankfurt → Darmstadt → Mannheim → Heidelberg → Karlsruhe → Stuttgart	Berlin → Potsdam → Magdeburg → Braunschweig → Hannover → Göttingen → Kassel → Fulda → Würzburg → Heidelberg → Karlsruhe → Stuttgart	Route 1 OD Pareto Solver
3	Hamburg → Hannover → Göttingen → Kassel → Fulda → Würzburg → Erlangen → Nuremberg → Ingolstadt → Munich → Salzburg	Hamburg → (Bremen) → Hannover → Göttingen → Kassel → Fulda → Würzburg → Erlangen → Nuremberg → Ingolstadt → (Augsburg) → Munich → Salzburg	Route 4 & 5 OD Pareto Solver
4	Paris → Marne-la-Vallée → Reims → Nancy → Strasbourg → Stuttgart → Ulm → Munich → Salzburg → Linz → St. Pölten → Vienna	Paris → Marne la Vallee → Reims → Saarbrücken → Mannheim → Darmstadt → Frankfurt → Würzburg → Erlangen → Nuremberg → Ingolstadt → Munich → Salzburg → Linz → St. Pölten → Vienna	Route 1 OD Pareto Solver
5	Paris → Marne-la-Vallée → Dijon → Lyon → Valence → Avignon → Aix-en-Provence → Marseille	Frejus → Toulon → Marseille → Aix en Provence → Avignon → Valence → Lyon → Dijon → Reims → Brüssel → Lüttich → Aachen → Colgone → Düsseldorf → Duisburg → Essen	104877 Pareto Solver

Benchmark Route #	Benchmark City Route	Comparing Solution Route	Origin of Solution Route
6	Marseille → Toulon → Fréjus → Nice → Turin → Milan → Venice → Ljubljana → Zagreb	Marseille → Aix en Provence → Avignon → Valence → Turin → Milan → Bologna → Venice → Udine → Villach → Klagenfurt → Ljubljana → Zagreb	Route 1 OD Pareto Solver
7	Amsterdam → Utrecht → Arnhem → Duisburg → Essen → Bochum → Leipzig → Dresden → Wrocław → Warsaw	Amsterdam → Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn → Göttingen → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan → Warszawa	80704 Pareto Solution

Table 16: Benchmark routes with corresponding Solution Route

6.6.1 Solution Benchmark Route 1

Benchmark Route 1	City Route	Time	Distance	Passengers carried/rejected	Total Revenue	Total cost	Total Profit	Profit margin
B	Vienna → St. Pölten → Linz → Passau → Plattling → Regensburg → Nürnberg → Erlangen → Würzburg → Frankfurt → Wiesbaden → Koblenz → Bonn → Köln → Düsseldorf → Duisburg	460	1603	747/1856	61945	24751	37194	60.0%
1 w_time (0.436) w_dist (0.092) w_profit (0.471)	Vienna → St. Pölten → Linz → Passau → Plattling → Regensburg → Nuremberg → Erlangen → Würzburg → Frankfurt → Wiesbaden → Koblenz → Bonn → Cologne → Düsseldorf → Duisburg	460 (0.0%)	1603 (0.0%)	747/1856 (0.0%)	61945 (0.0%)	24751 (0.0%)	37194 (0.0%)	60.0% (0.0%)
2 w_time (0.317) w_dist (0.295) w_profit (0.388)	Vienna → St. Pölten → Linz → Salzburg → Munich → Ingolstadt → Nuremberg → Erlangen → Würzburg → Frankfurt → Wiesbaden → Koblenz → Bonn → Cologne → Düsseldorf → Duisburg	459 (-0.1%)	1769 (+10.3%)	778/1938 (+4.1%) (+4.4%)	62751 (+1.3%)	24236 (-2.0%)	38515 (+3.5%)	61.4% (+2.3%)

Table 17: Benchmark route 1 with corresponding Solution Route 1

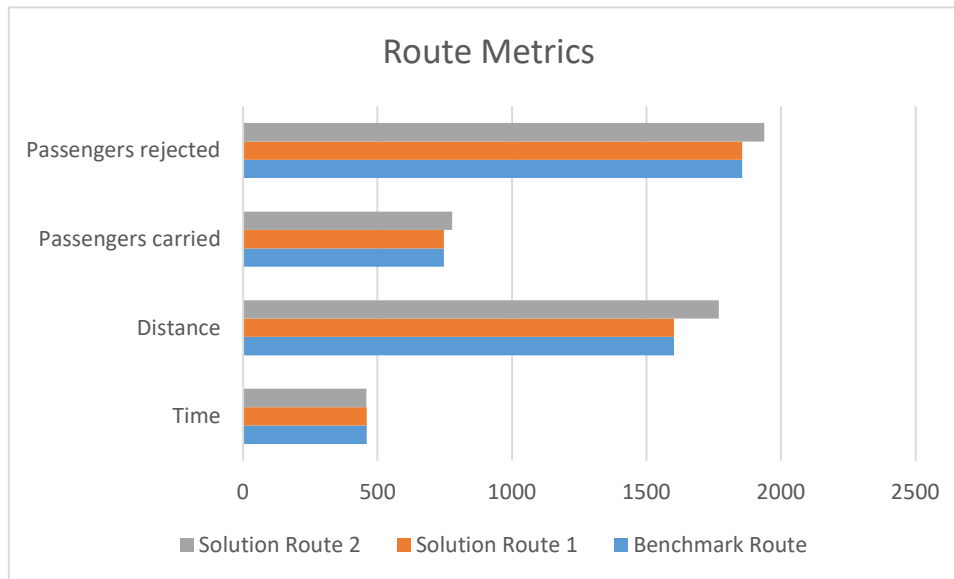


Figure 19: Route metrics for Solution of Benchmark Route 1

Duisburg via Linz, Passau, Regensburg, Nuremberg, Würzburg and Frankfurt, with a travel time of 460 minutes, a distance of 1,603 km, and 747 passengers carried against 1,856 rejected. The service generates a total revenue of 61,945 €, incurs costs of 24,751 €, and thus yields a substantial profit of 37,194 €, corresponding to a profit margin of 60.0% (Table 17). From a line planning perspective, this indicates that the benchmark route is highly profitable under the modeled demand and cost structure, but the high number of rejected passengers reveals a significant capacity bottleneck: demand clearly exceeds the available train capacity, so the achieved profit is accompanied by a considerable amount of unmet demand along this corridor.

The second solution (Row 2) maintains the same origin and destination but follows an alternative alignment via Salzburg, Munich, and Ingolstadt before rejoining the original corridor in Nuremberg. This variant is slightly faster (459 vs. 460 minutes) but longer in distance (1,769 vs. 1,603 km), which implies additional infrastruc-

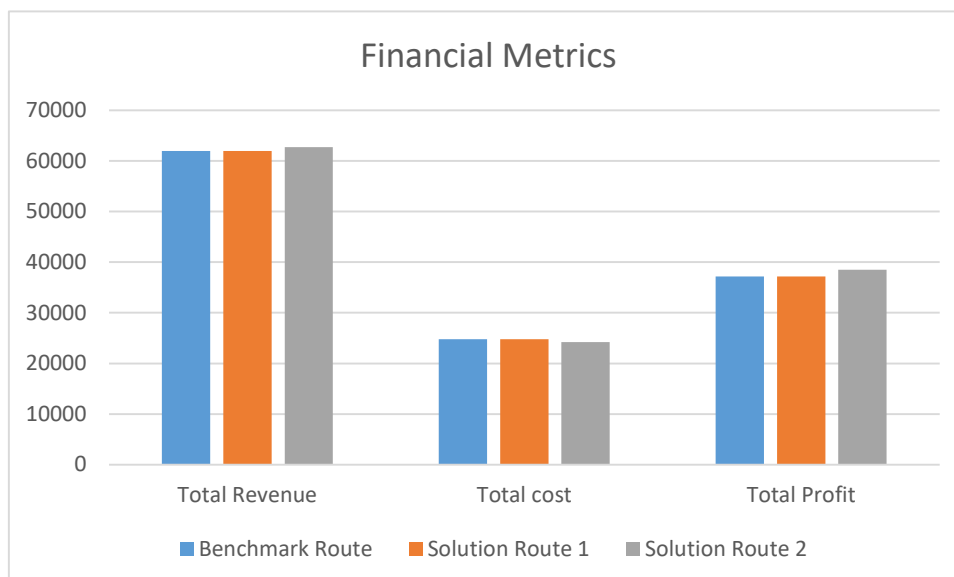


Figure 20: Financial metrics for Solution of Benchmark Route 1

higher total revenue of 62,751 €, slightly lower cost level of 24,236 €, and a correspondingly increased profit of 38,515 € with a profit margin of 61.4% (Figure 20). In other words, the alternative routing sacrifices geometric efficiency (more kilometers traveled) in favor of better revenue potential, leveraging strong intermediate markets while keeping travel time practically unchanged. Comparing the two, the model identifies that both routings are highly profitable, but the variant via

The results for Benchmark Route 1 show that the optimization model is able to exactly reproduce the benchmark alignment and, at the same time, suggest a slightly modified but financially superior variant. Rows B and 1 are identical in all dimensions: they correspond to the original benchmark relation from Vienna to

additional infrastructure usage and energy costs. Despite the longer distance, the route carries more passengers (778) and also rejects more (1,938), which suggests that the detour via major hubs such as Munich provides access to additional high-yield demand (Figure 19). This is reflected in the

Salzburg–Munich–Ingolstadt marginally outperforms the benchmark in terms of absolute profit and margin, at the expense of longer network occupation and still very high levels of unsatisfied demand.

6.6.2 Solution Benchmark Route 2

Benchmark Route 2	City Route	Time	Distance	Passen- gers car- ried/re- jected	Total Reve- nue	Total cost	Total Profit	Profit margin
B	Berlin → Potsdam → Magde- burg → Halle → Erfurt → Fulda → Frankfurt → Darm- stadt → Mannheim → Heidel- berg → Karlsruhe → Stuttgart	478	1228.1	733/427	52994	23320	29674	56.0%
1 w_time (0.241) w_dist (0.343) w_profit (0.416)	Berlin → Potsdam → Magde- burg → Braunschweig → Hannover → Göttingen → Kassel → Fulda → Würzburg → Heidelberg → Karlsruhe → Stuttgart	461 (-3.5%)	1369.9 (+11.5%)	731/291 (-0.1%) (-31.8%)	53433 (+0.1%)	25814 (+10.6%)	27619 (-6.9%)	51.7% (-7.6%)

Table 18: Benchmark route 2 with corresponding Solution Route 2

The comparison between the benchmark route and the proposed solution route reveals several important distinctions concerning operational characteristics, demand patterns, and financial performance. The solution route achieves a shorter overall travel time of 461 minutes compared to 478 minutes on the benchmark route, despite its longer physical distance of 1369.9 km instead of 1228.1 km (Table 18). This suggests that the alternative alignment benefits from faster infrastructure segments, most notably the Hannover–Göttingen high-speed corridor, which replaces the slower Halle–Erfurt and Erfurt–Fulda sections used in the benchmark. The resulting reduction in travel time enhances the attractiveness of the service, particularly for long-distance passengers, and helps maintain a similar effective demand level despite the deviation from the original corridor.

In terms of passenger volumes and capacity utilization, both routes carry almost the same number of passengers, with 733 on the benchmark and 731 on the solution route. However, the number of rejected passengers differs significantly: the benchmark route rejects 427 potential passengers, whereas the solution route rejects only 291 (Figure 21). This indicates that the solution alignment distributes demand more evenly and avoids the severe bottlenecks present in the benchmark’s central German sections, particularly around Erfurt, Halle, and Leipzig, where peak loads exceed available capacity. The improved balance of demand achieved by the solution route enhances service quality and reduces unmet travel needs, which is an important consideration for long-distance network planning.

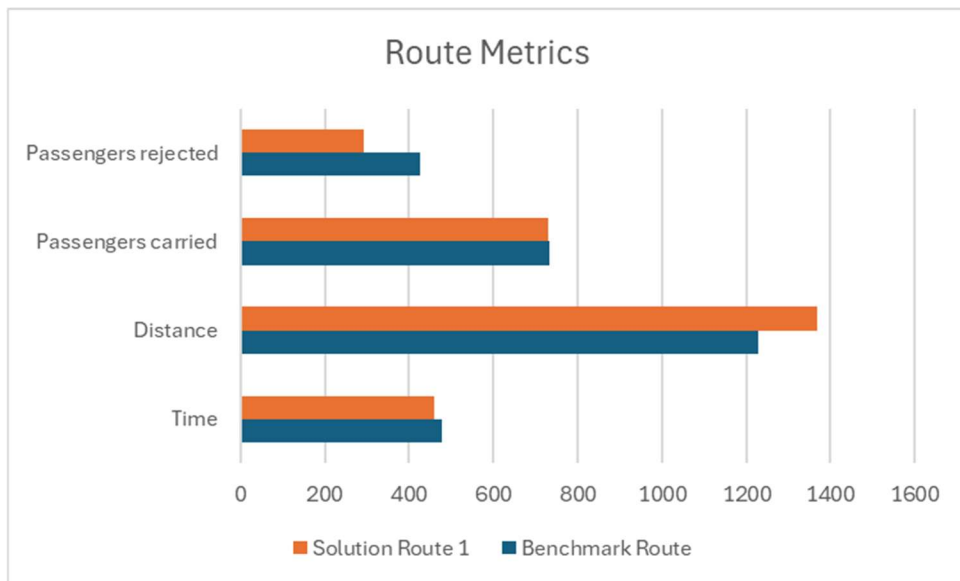


Figure 21: Route metrics for Solution of Benchmark Route 2

The revenue performance of the two routes is very similar, although the solution route performs slightly better, generating €53,433 compared to the benchmark route's €52,994 (Figure 22). This modest advantage can be attributed to the characteristics of the cities served by the solution route. Passing through Hanno-

ver and the surrounding high-demand regions tends to attract passengers with higher willingness to pay and more frequent business travel, which increases average revenue per passenger. Although this difference is not large, it nonetheless indicates that the alternative alignment may possess stronger long-term revenue potential.

The cost structure of the solution route represents its main disadvantage. With a total operating cost of €25,814 compared to €23,320 on the benchmark route, the solution incurs noticeably higher expenses. This is largely the consequence of its longer distance and the passage through additional major junctions such as Hannover,

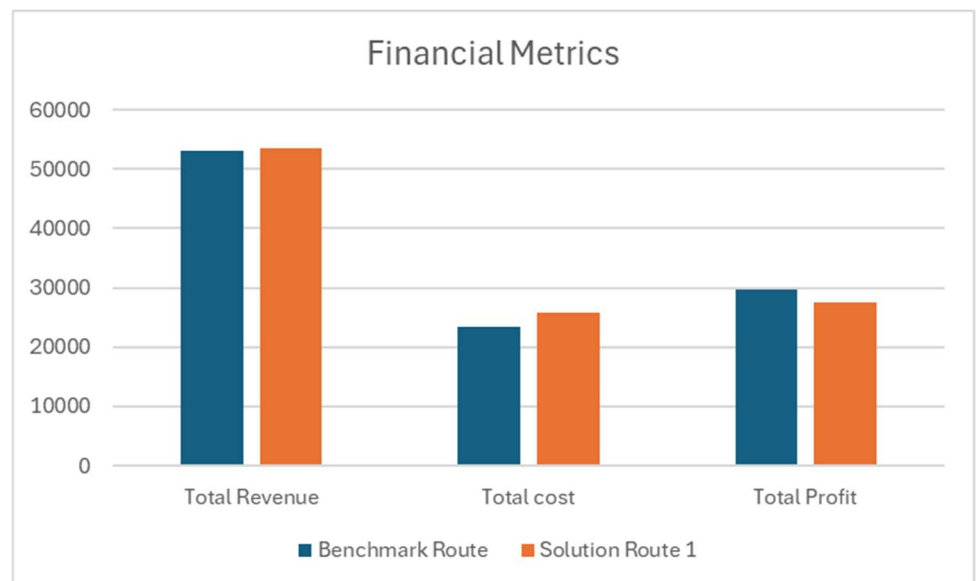


Figure 22: Financial metrics for Solution of Benchmark Route 2

where infrastructure charges are generally higher. Despite this, the increase in costs is moderate and does not negate the benefits created by reduced passenger rejection and increased revenue.

Profitability remains strong for both services, although the benchmark route performs slightly better. The benchmark achieves an operating profit of €29,674 at a margin of 56.0 percent, while the solution generates €27,619 with a 51.7 percent margin. While the benchmark route is therefore more economically efficient, the difference is relatively small, and the solution route still demonstrates robust operational performance. The slight reduction in profit margin is primarily due to the higher operating costs rather than any underlying weakness in demand.

From a broader network perspective, the solution route addresses several shortcomings of the benchmark alignment. It shortens travel time, reduces the extent of rejected passengers, and offers a marginally higher revenue outcome. For operators aiming to improve service reliability, passenger satisfaction, and long-term ridership growth, these advantages may carry greater strategic value than the moderate loss of profit margin. Furthermore, the solution route aligns more closely with the contemporary structure of Germany's north–south high-speed rail network, which favors the Hannover–Göttingen–Kassel axis for high-capacity long-distance movements.

In conclusion, while the benchmark route remains the more financially efficient corridor, the solution route presents a number of strategic improvements. Its shorter travel time, more favorable capacity distribution, and slightly stronger revenue performance make it a compelling alternative, particularly in contexts where service quality and demand fulfillment are prioritized alongside financial outcomes. The solution route therefore represents a viable and forward-looking enhancement to the existing alignment, offering clear benefits without compromising overall economic sustainability.

6.6.3 Solution Benchmark Route 3

Benchmark Route 3	City Route	Time	Distance	Passen- gers car- ried/re- jected	Total Revenue	Total cost	Total Profit	Profit margin
B	Hamburg → Hannover → Göttingen → Kassel → Fulda → Würzburg → Nuremberg → Ingolstadt → Munich → Salzburg	358	1398.7	661/389	50139	26388	23751	47.4%
1 w_time (0.436) w_dist (0.092) w_profit (0.471)	Hamburg → Bremen → Hannover → Göttingen → Kassel → Fulda → Würzburg → Erlangen → Nuremberg → Ingolstadt → Augsburg → Munich → Salzburg	416 (+16.2%)	1596 (+14.1%)	731/742 (+10.5%) (+90.7%)	56864 (+13.4%)	30113 (+14.1%)	26751 (+12.6%)	47.0% (-0.1%)
2 w_time (0.326) w_dist (0.416) w_profit (0.259)	Hamburg → Hannover → Göttingen → Kassel → Fulda → Würzburg → Erlangen → Nuremberg → Ingolstadt → Munich → Salzburg	358 (0.0%)	1398.7 (0.0%)	661/389 (0.0%)	50139 (0.0%)	26388 (0.0%)	23751 (0.0%)	47.4% (0.0%)

Table 19: Benchmark route 3 with corresponding Solution Route 3

The comparison between the benchmark route and the two proposed solution routes highlights several distinct operational and financial characteristics, ultimately showing that the solver validates the benchmark alignment as the most efficient configuration. The benchmark route and Solution Route 2 are in fact

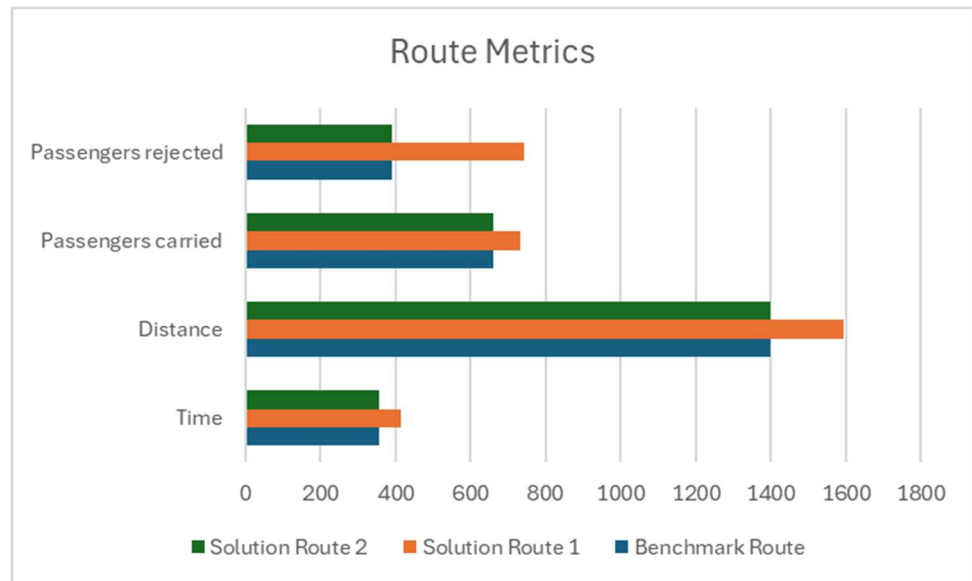


Figure 23: Route metrics for Solution of Benchmark Route 3

identical in both structure and performance, which demonstrates that the optimization process effectively reconfirmed the existing routing as the optimal choice under the modeled assumptions (Table 19). Both routes operate over a distance of 1,398.7 kilometres with a total travel time of 358 minutes, and both carry the same number of passengers, namely 661, while rejecting 389 passengers due to capacity limitations. Their financial indicators also match exactly, yielding €50,139 in revenue, €26,388 in total costs, and an operating profit of €23,751, resulting in an operating margin of 47.4 percent. This perfect alignment in operational and financial outcomes confirms that the current corridor structure is already well-positioned within the network and that no alternative alignment examined by the solver was able to produce superior performance.

Solution Route 1 differs more substantially from both the benchmark and Solution Route 2. It extends the route length to 1,596 kilometres and increases the total travel time to 416 minutes by routing the service through Bremen and adding additional stops such as Erlangen and Augsburg. While this expanded alignment results in a higher transported passenger volume of 731, demand pressure also intensifies dramatically, leading to 742 rejected passengers, which is nearly double the number observed on the benchmark corridor (Figure 23). This indicates that the alternative path introduces new demand hotspots or amplifies existing bottlenecks, particularly in the northern and southern sections of the route. Although the route generates higher total revenue of €56,864, the greater operational distance and additional infrastructure sections drive costs upwards to €30,113, thereby reducing the net profit advantage. The resulting operating profit of €26,751 remains slightly above the benchmark, but the margin falls marginally to 47.0 percent, illustrating that the financial gains obtained from additional transported passengers are largely offset by the increased cost burden (Figure 24).

When comparing all three alternatives, it becomes clear that the benchmark configuration strikes the most balanced relationship between operational efficiency, capacity utilisation, and financial sustainability. Solution Route 1 achieves a higher overall revenue, but this advantage is counteracted by increased costs and substantial capacity shortfalls, which ultimately reduce its attractiveness as an operational alternative. By contrast, the identical performance of the benchmark

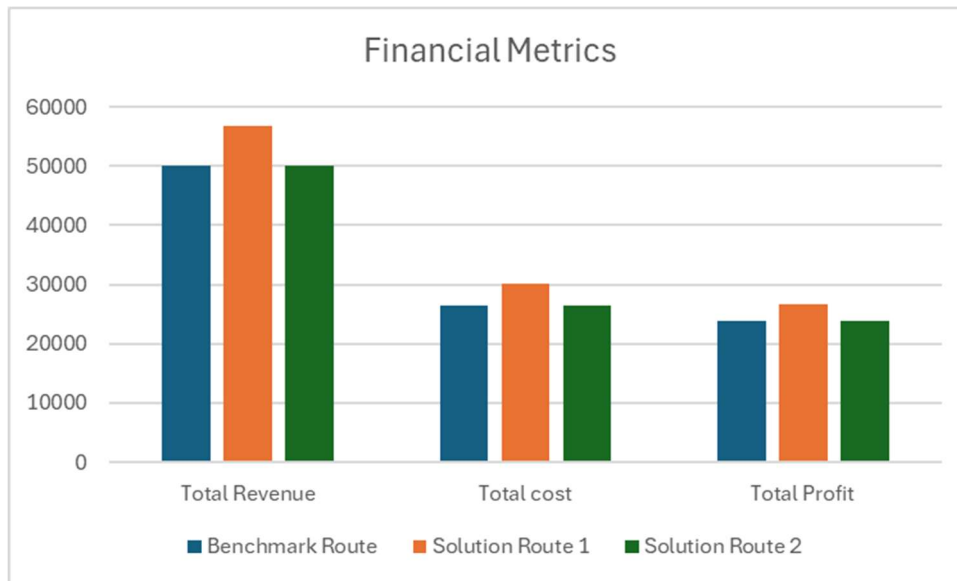


Figure 24: Financial metrics for Solution of Benchmark Route 3

route and Solution Route 2 shows that the optimisation model, even when exploring alternative topologies, converges back to the current infrastructure-aligned corridor as the most favourable solution. This outcome underscores that the existing Hamburg–Hannover–Göttingen–Kassel–Fulda–Würzburg–

Nuremberg–Ingolstadt–Munich–Salzburg alignment already represents the most efficient configuration given current demand conditions, capacity constraints, and infrastructure characteristics.

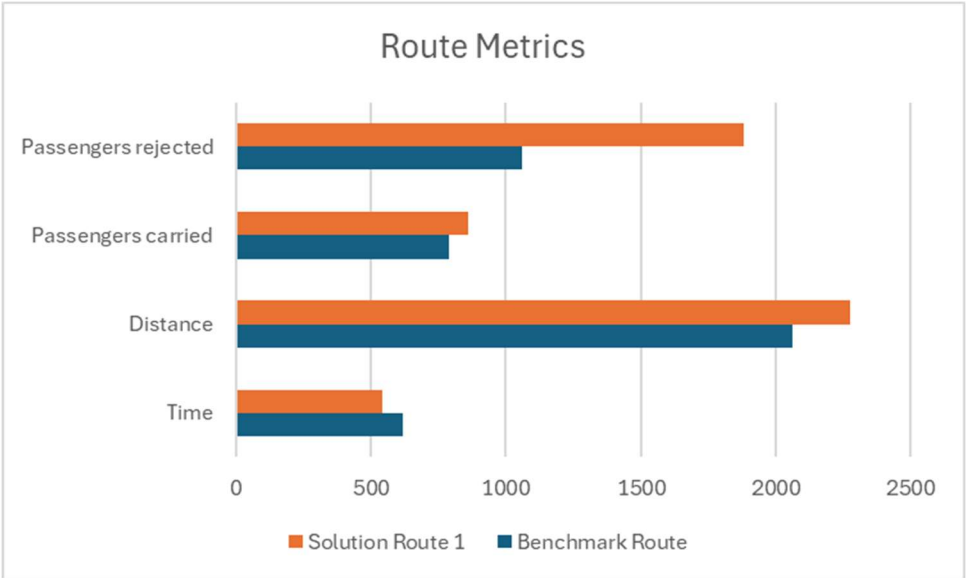
Overall, the analysis confirms that the benchmark route remains the optimal choice within the evaluated network environment. The solver's replication of this result in Solution Route 2 provides strong validation for the robustness of the existing long-distance structure, while the markedly inferior balance of demand and cost in Solution Route 1 emphasises the importance of minimising unnecessary route extensions and avoiding congestion-prone segments. The findings therefore demonstrate that the current Hamburg–Salzburg corridor is not only operationally efficient but also financially well-calibrated, reaffirming its role as a stable backbone of north–south high-speed connectivity.

6.6.4 Solution Benchmark Route 4

Benchmark Route 4	City Route	Time	Distance	Passengers carried/rejected	Total Revenue	Total cost	Total Profit	Profit margin
B	Paris → Marne-la-Vallée → Reims → Nancy → Strasbourg → Stuttgart → Ulm → Munich → Salzburg → Linz → St. Pölten → Vienna	618	2064.1	790/1058	85081	26937	58144	68.3%
1 w_time (0.345) w_dist (0.564) w_profit (0.091)	Paris → Marne la Vallee → Reims → Saarbrücken → Mannheim → Darmstadt → Frankfurt → Würzburg → Erlangen → Nuremberg → Ingolstadt → Munich → Salzburg → Linz → St. Pölten → Vienna	543 (-12.1%)	2277.8 (10.3%)	862/1881 (+9.1%) (+77.7%)	90114 (+5.9%)	32998 (+22.5%)	57116 (-1.7%)	63.4% (-7.1%)

Table 20: Benchmark route 4 with corresponding Solution Route 4

The comparison between the benchmark alignment of the Paris–Vienna corridor and the proposed solution route reveals substantial differences in routing logic, operational performance, and the resulting financial outcomes. The benchmark route follows a long-established international axis that connects Paris with Vienna via Reims, Nancy, Strasbourg, Stuttgart, Ulm, Munich, and Salzburg, covering a distance of 2,064.1 kilometres with a total travel time of 618 minutes. Solution Route 1 modifies this structure by diverting the train after Reims toward Saarbrücken, then continuing through Mannheim, Darmstadt, Frankfurt, Würzburg, Erlangen, and Nuremberg before rejoining the benchmark alignment at Munich. This modification increases the total route length to 2,277.8 kilometres while reducing the overall travel time to 543 minutes, suggesting that the solution corridor leverages faster infrastructure segments in southwestern Germany at the cost of extending the route geographically (Table 20).



From a demand perspective, the solution route manages to transport more passengers than the benchmark - 862 compared with 790 - indicating that the alternative alignment intersects stronger regional demand centres along the Rhine/Main axis, particularly in Mannheim, Darmstadt, and Frankfurt (Figure 25).

Figure 25: Route metrics for Solution of Benchmark Route 4

At the same time, however, the number of rejected passengers rises dramatically from 1,058 on the benchmark to 1,881 on the solution route. This suggests that although the alternative configuration passes through more populous regions, it also introduces greater load concentration in segments that are already capacity constrained, leading to substantial unmet demand. The increase in rejected passengers reflects more pronounced bottlenecks, especially in the Frankfurt–Würzburg–Nuremberg corridor, which is known for its heavy utilisation in both domestic and international long-distance traffic.

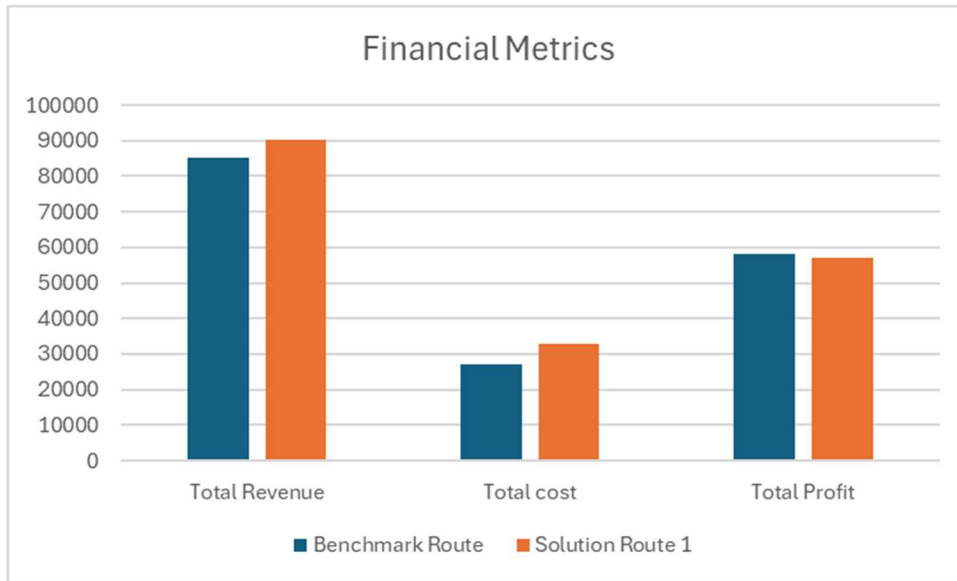


Figure 26: Financial metrics for Solution of Benchmark Route 4

Financially, the solution route generates higher total revenue than the benchmark, reaching €90,114 compared with the benchmark's €85,081 (Figure 26). This increase is consistent with the stronger demand and the higher number of boardings observed along the Rhine/Main metropolitan corridor. However, the ex-

tended route length and the additional high-cost sections - particularly those involving the Mannheim–Frankfurt and Frankfurt–Würzburg segments - lead to a significant rise in total operating costs from €26,937 on the benchmark to €32,998 on the solution route. As a result, despite the higher revenue intake, the overall profitability of the solution route does not surpass the benchmark. The benchmark achieves a total profit of €58,144 and an operating margin of 68.3 percent, whereas the solution route achieves a slightly lower absolute profit of €57,116 and a reduced margin of 63.4 percent. Thus, the benchmark route remains more cost-efficient, with higher profitability relative to its cost base.

The comparison also shows that the modifications introduced in Solution Route 1 lead to a mixed operational picture. On one hand, the significantly reduced travel time makes the corridor more competitive from a passenger perspective and may favor future ridership growth. On the other hand, the increased distance and the sharper rise in rejected passengers indicate that the solution route puts additional pressure on infrastructure segments that are already traffic-heavy, reducing service accessibility and worsening capacity-related performance indicators. This trade-off between speed and accessibility suggests that the solution route may not consistently outperform the established international corridor, particularly when evaluated in terms of network-wide efficiency.

Overall, the benchmark route remains the more balanced and economically efficient option despite its longer travel time. It offers a better match between demand and available capacity, generates fewer rejected passengers, and operates at a higher profit margin while still serving major international hubs. The solution route demonstrates that alternative alignments through southwestern Germany can unlock additional revenue potential but also introduces drawbacks in the form of higher operational costs, increased congestion, and reduced profitability. For these reasons, the solution route does not present a clear improvement over the benchmark alignment, and the solver's results reinforce the strength and efficiency of the original Paris–Vienna configuration as the best-performing long-distance cross-border option under the modeled assumptions.

6.6.5 Solution Benchmark Route 5

Bench- mark Route 5	City Route	Time	Distance	Passen- gers car- ried/re- jected	Total Reve- nue	Total cost	Total Profit	Profit margin
B	Paris → Marne-la-Vallée → Dijon → Lyon → Valence → Avignon → Aix-en-Provence → Marseille	369	1315.1	486/0	41798	16906	24892	59.6%
1 w_time (0.108) w_dist (0.090) w_profit (0.803)	Frejus → Toulon → Mar- seille → Aix en Provence → Avignon → Valence → Lyon → Dijon → Reims → Brüssel → Lüttich → Aachen → Köln → Düsseldorf → Duis- burg → Essen	747 (+102%)	2372.3 (+80.3%)	770/1995 (+58.4%) (+1995)	93857 (+124%)	32134 (+90.0%)	61724 (+147%)	65.8% (+10.4%)

Table 21: Benchmark route 5 with corresponding Solution Route 5

The comparison between the benchmark configuration of the Paris–Marseille high-speed corridor and the proposed solution route reveals a pronounced contrast in both operational characteristics and commercial performance. The benchmark route represents the archetypal French domestic high-speed alignment, operating entirely within a unified national system and linking Paris with Marseille through only a handful of strategic intermediate stops. It covers 1,315.1 kilometres in 369 minutes, transports 486 passengers without any rejected demand, and generates €41,798 in revenue at an operating cost of €16,906, which results in a profit of €24,892 and a profit margin of 59.6 percent (Table 21). These values reflect a stable and well-balanced corridor in which demand aligns neatly with available capacity, travel times remain low, and operational costs are contained through the use of the core LGV Sud-Est and LGV Méditerranée infrastructure.

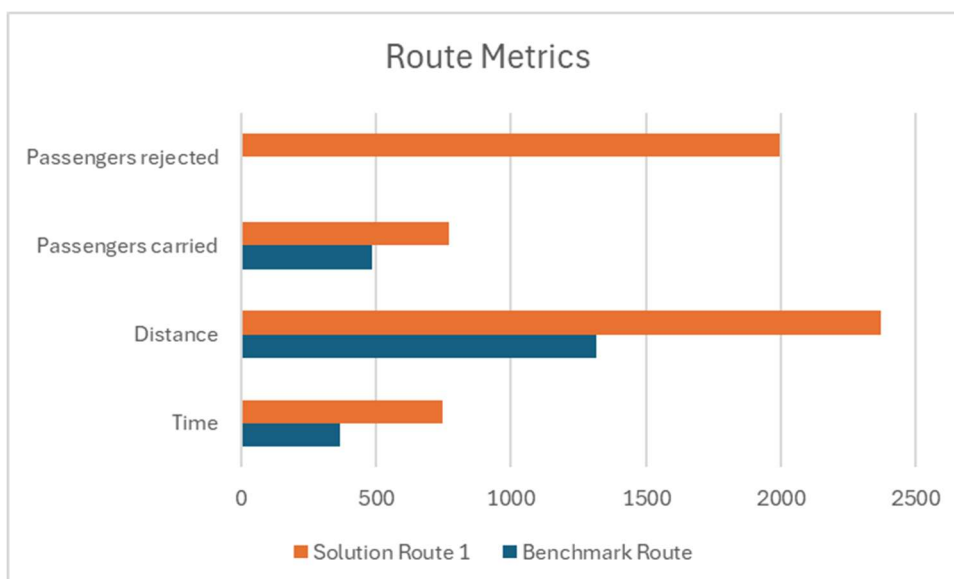


Figure 27: Route metrics for Solution of Benchmark Route 5

The solution route represents a fundamentally different approach. Rather than following a compact north–south alignment within France, it constructs a long international arc extending from the Mediterranean coast into Belgium and western Germany, connecting cities such as

Reims, Brussels, Liège, Aachen, Cologne, Düsseldorf, Duisburg, and Essen. This reconfiguration nearly doubles the overall route length to 2,372.3 kilometres and extends the total travel time to 747 minutes. The route's expansive geographical reach reshapes demand significantly, attracting 770 transported passengers - far more than on the benchmark - but at the same time overwhelming available capacity to the extent that 1,995 passengers are rejected (Figure 27). Such a high level of unmet demand illustrates that although the extended alignment intersects dense metropolitan areas in France, Belgium, and Germany, the resulting load concentration exceeds the carrying capacity of a single long-distance service operating over the corridor.

Financially, the solution route exhibits both strengths and weaknesses. It generates €93,857 in revenue, far surpassing the benchmark's €41,798. This dramatic increase reflects the large urban markets it connects and the high passenger interest along the international axis toward Brussels, Cologne, and the

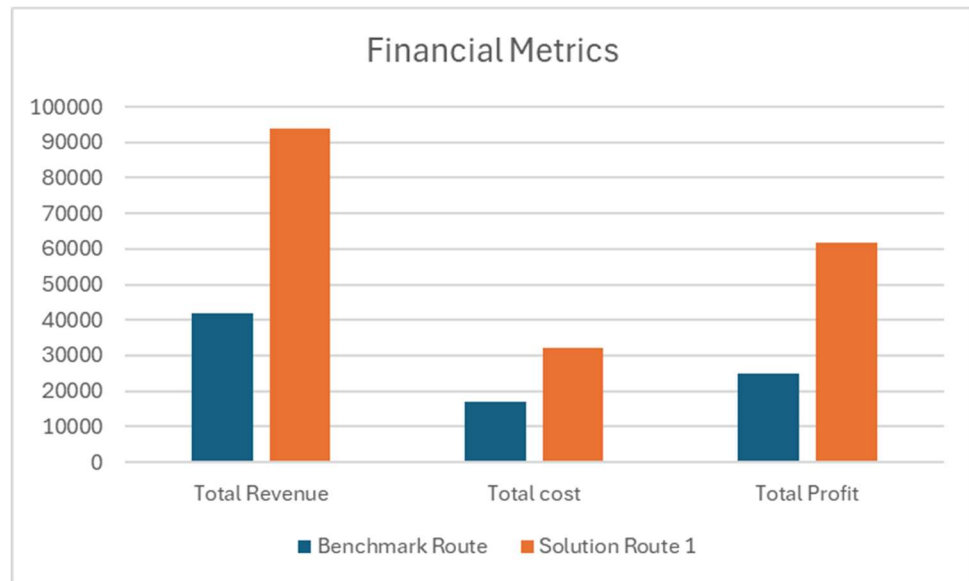


Figure 28: Financial metrics for Solution of Benchmark Route 5

Rhine-Ruhr area. However, the extensive distance and the use of infrastructure in multiple countries substantially elevate operational expenses. Total costs rise to €32,134, which is nearly double the cost of the benchmark route (Figure 28). Even so, the solution route remains highly profitable, achieving €61,724 in operating profit and a profit margin of 65.8 percent. This margin exceeds the benchmark's 59.6 percent, demonstrating that the significantly higher revenue more than compensates for the steep increase in cost. The solution route is therefore not only commercially viable but financially superior to the benchmark, despite its much higher operational burden.

Nevertheless, the operational drawbacks of the solution alignment are substantial. The large number of rejected passengers indicates that the corridor, in its proposed form, suffers from major capacity bottlenecks, especially through the northern French, Belgian, and western German metropolitan regions. These bottlenecks diminish the service quality and highlight that a single long-distance train cannot adequately capture the dense demand along this international arc. Moreover, the doubling of travel time diminishes the attractiveness of the route as a point-to-point Paris–Marseille service, suggesting that its role within the network would shift away from long-distance anchoring and toward functioning as a multi-market international connector.

Taken together, the benchmark and the solution route represent two fundamentally different strategic visions. The benchmark route excels in efficiency, speed, and domestic network coherence, offering a high-quality service tailored to French interregional demand. The solution route, by contrast, prioritises network reach and revenue generation, using an international path to tap into multiple densely populated markets at the cost of increased distance, longer travel times, and substantial capacity strain. While the solution route outperforms the benchmark financially, the premium comes with significant operational complexity and large volumes of rejected demand,

suggesting that it would require additional capacity - either through increased frequency or larger rolling stock - to function satisfactorily in practice.

In summary, the solution route achieves a remarkable financial result but does so by dramatically expanding the corridor's geographic scope and absorbing heavy demand from several international markets. The benchmark route, though more modest in scale, remains the more balanced and operationally coherent alternative. The comparison therefore highlights a key tension in long-distance line planning: routes that maximise revenue and market coverage are not necessarily those that provide the most reliable or capacity-efficient service.

6.6.6 Solution Benchmark Route 6

Bench- mark Route 6	City Route	Time	Distance	Passen- gers car- ried/re- jected	Total Revenue	Total cost	Total Profit	Profit margin
B	Marseille → Toulon → Fréjus → Nice → Turin → Milan → Venice → Ljubljana → Zagreb	1074	1850.6	687/273	49161	20262	28899	58.8%
1 w_time (0.480) w_dist (0.141) w_profit (0.379)	Marseille → Aix en Pro- vence → Avignon → Va- lence → Turin → Milan → Bologna → Venice → Udine → Villach → Kla- genfurt → Ljubljana → Zagreb	951 (-11.4%)	2382.8 (+28.7%)	802/683 (+16.7%) (+150%)	60806 (+23.6%)	24785 (+22.3%)	36021 (24.6%)	59.2% (+0.1%)

Table 22: Benchmark route 6 with corresponding Solution Route 6

The comparison between the benchmark Marseille–Zagreb corridor and the proposed solution route illustrates how different routing decisions shape both operational performance and financial outcomes along this long, transnational axis. The benchmark route follows a direct Mediterranean-to-Balkan alignment, passing through the coastal French cities before climbing toward

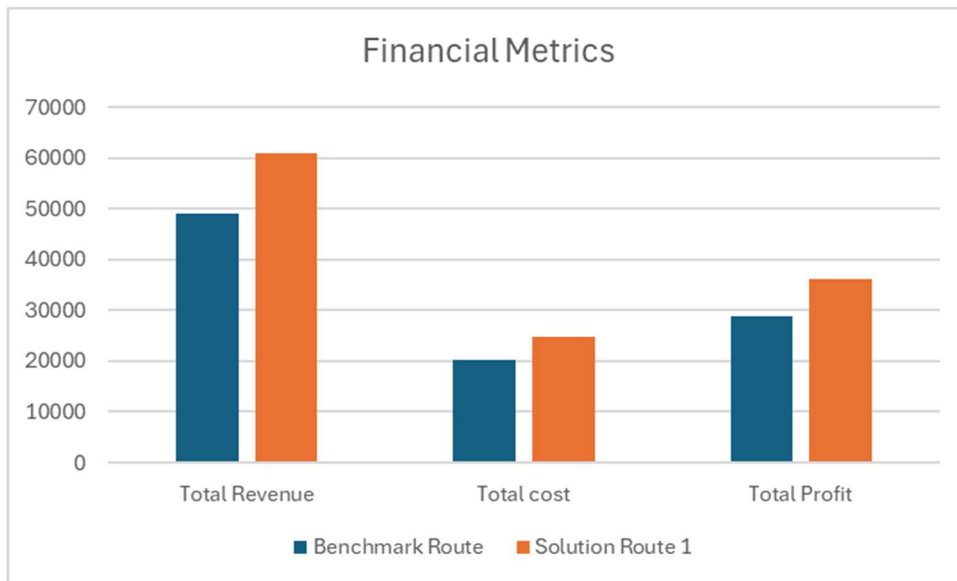


Figure 29: Financial metrics for Solution of Benchmark Route 6

ble 22). Financially, the benchmark route generates €49,161 in revenue, incurs operating costs of €20,262, and achieves a healthy operating profit of €28,899 with a profit margin of 58.8 percent (Figure 29). These values reflect a route that is both operationally feasible and economically attractive while maintaining a relatively balanced relationship between demand and available capacity.

The solution route represents a more ambitious reconfiguration. Instead of moving along the southern French coast, it begins inland at Marseille and proceeds northward through Aix-en-Provence, Avignon, and Valence before crossing into Italy toward Turin and Milan. From there, it follows a much broader Italian arc through Bologna, Venice, Udine, and Villach toward Klagenfurt, Ljubljana, and finally Zagreb. This adjustment extends the route length substantially to 2,382.8 kilometres but reduces total travel time to 951 minutes, suggesting that the service capitalises on faster, more modern railway infrastructure in the Italian high-speed network (Figure 30). The longer geographical footprint exposes the route to a wider array of metropolitan regions, particularly in northern Italy, which has one of Europe's densest rail markets. As a result, the solution route transports significantly more passengers - 802 in total - but simultaneously rejects 683 travellers, more than double the number observed on the benchmark. This indicates that the broader alignment intersects several high-demand corridors that a single service cannot fully accommodate.

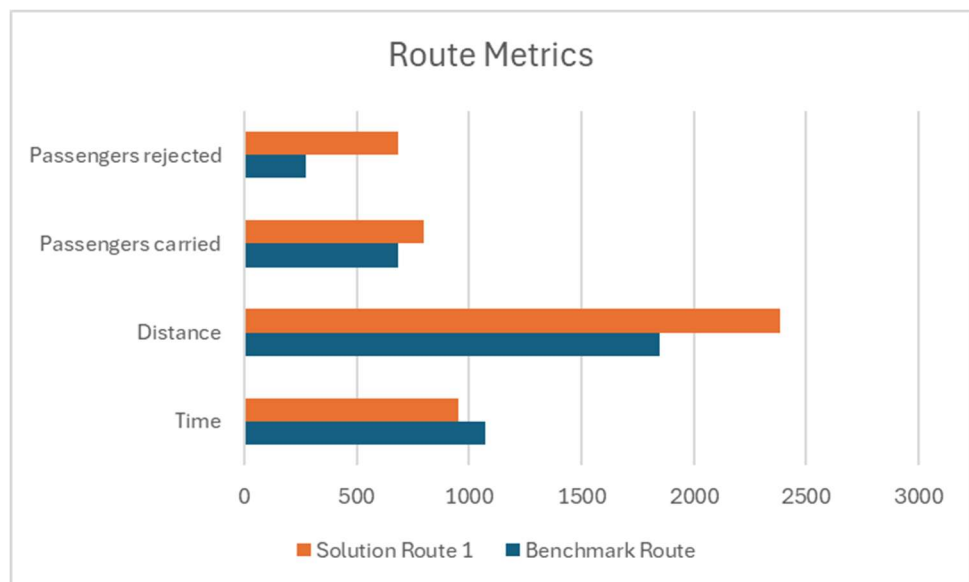


Figure 30: Route metrics for Solution of Benchmark Route 6

northern Italy and then continuing eastward through Milan, Venice, Ljubljana, and finally Zagreb. This configuration covers 1,850.6 kilometres and requires 1,074 minutes of total travel time. Under the modeled conditions, it carries 687 passengers and rejects 273 additional travellers due to capacity limitations (Table 22).

In financial terms, the solution route outperforms the benchmark in both total revenue and absolute profit. Revenue increases markedly to €60,806, reflecting the strong market potential in the additional cities served. However, the extended length and the need to operate across multiple costly Italian infrastructure segments raise operating costs to €24,785. Despite this increase, the solution route still generates a higher total profit of €36,021 and achieves a slightly better profit margin of 59.2 percent. The improvement in profitability shows that the revenue gains associated with tapping into economically strong regions outweigh the added operational expenses and the increased distance. This also suggests that, in principle, long-distance services that integrate multiple high-density markets can achieve superior financial performance even when their alignment becomes more complex and stretched geographically.

The increase in rejected passengers highlights an important operational weakness of the solution design. The significantly higher unmet demand reveals systemic bottlenecks in segments such as Milan–Bologna and Bologna–Venice, where the flow of passengers from regional and long-distance networks converges. While the benchmark route also experiences some degree of capacity strain, its more linear alignment distributes demand more evenly, reducing pressure on any single corridor. The solution route, in contrast, collects intense demand from several Italian metropolitan nodes, leading to sharp capacity mismatches that diminish service accessibility despite stronger overall ridership levels.

Taken together, the two routes represent distinct strategic approaches to transnational connectivity. The benchmark route prioritises a direct and coherent Mediterranean-to-Central Europe axis that offers a balanced mix of operational simplicity, moderate demand, and stable profitability. The solution route, by contrast, is economically more successful but operationally more strained. It leverages high-demand markets to boost total revenue and profit, yet its expanded corridor introduces longer travel distances, higher infrastructure costs, and considerable unmet demand. These characteristics suggest that while the solution route offers financial advantages, it would require either larger trainsets or increased service frequency to operate effectively within the real-world constraints of capacity and demand.

In conclusion, the solution route provides a financially superior alternative but at the cost of increased complexity and reduced operational balance. The benchmark alignment remains the more consistent and manageable option, whereas the solution route's performance demonstrates the latent potential of a wider international footprint - potential that can only be fully realised through corresponding enhancements in capacity provision and service planning.

6.6.7 Solution Benchmark Route 7

Benchmark Route 7	City Route	Time	Distance	Passengers carried/ rejected	Total Revenue	Total cost	Total Profit	Profit margin
B	Amsterdam → Utrecht → Arnhem → Duisburg → Essen → Bochum → Leipzig → Dresden → Wrocław → War- saw	964	2371.7	753/1753	92553	37245	55308	59.8%

Bench- mark Route 7	City Route	Time	Dis- tance	Passen- gers car- ried/re- jected	Total Revenue	Total cost	Total Profit	Profit margin
1 w_time (0.411) w_dist (0.179) w_profit (0.410)	Amsterdam → Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn → Göttingen → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poz- nan → Warsaw	879 (-8.8%)	2469.4 (+4.1%)	755/2167 (+0.1%) (+23.6%)	101827 (+10.0%)	37170 (-0.1%)	64657 (+16.9%)	63.5% (+6.1%)

Table 23: Benchmark route 7 with corresponding Solution Route 7

The comparison between the benchmark Amsterdam–Warsaw corridor and the proposed solution

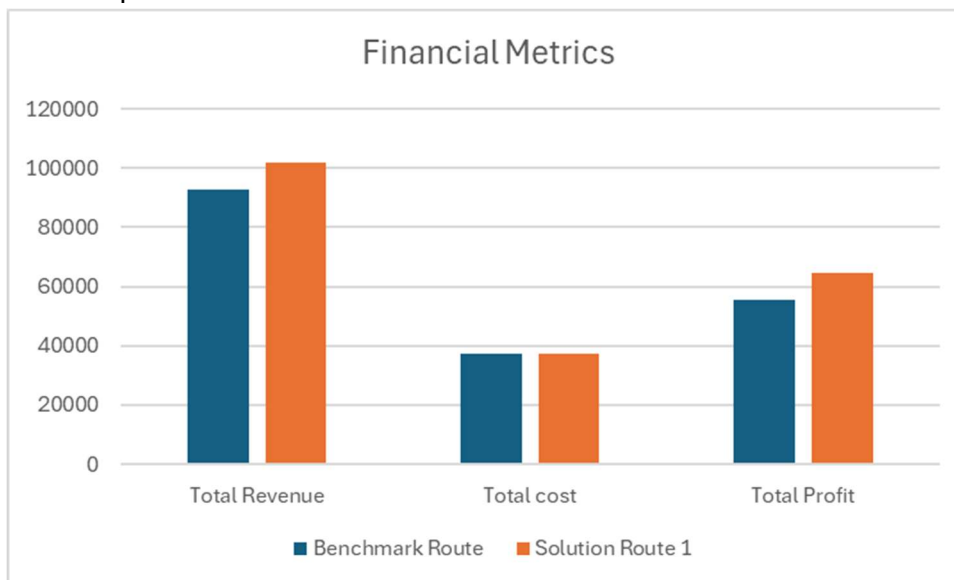


Figure 31: Financial metrics for Solution of Benchmark Route 7

route reveals substantial structural differences in both route design and network function, which directly shape the operational and financial performance of the two alternatives. The benchmark route represents a relatively direct north–east axis through the Netherlands, western Germany, and Poland, follow-

ing major urban nodes such as Utrecht, Arnhem, Duisburg, Essen, Bochum, Leipzig, Dresden, and Wrocław before terminating in Warsaw. It spans 2,371.7 kilometres with a total travel time of 964 minutes and carries 753 passengers while rejecting 1,753 due to capacity limitations (Table 23). Financially, it generates €92,553 in revenue at a total operating cost of €37,245, resulting in a profit of €55,308 and a profit margin of 59.8 percent (Figure 31). These results reflect a route that is both commercially strong and operationally manageable, even though the level of rejected passengers indicates persistent bottlenecks in the German and western Polish sections.

The solution route reconfigures the corridor considerably. After leaving Amsterdam, it passes through Arnhem and continues via Duisburg but then diverges through Düsseldorf, Wuppertal, Hagen, Hamm, and Paderborn, shifting the early part of the route deeper into the Rhine–Ruhr area. It then proceeds toward Göttingen, Braunschweig, Magdeburg, Potsdam, and Berlin, before extending northeast to Stettin and then eastward to Poznań and Warsaw. This redesigned alignment increases the total geographical distance to 2,469.4 kilometres, yet reduces travel time substantially to 879 minutes (Figure 32). The faster running time indicates that the solution corridor makes greater use of optimized infrastructure, particularly on the German high-speed spine between Göttingen, Braunschweig, and Berlin, as well as the long straight sections across northern Poland.

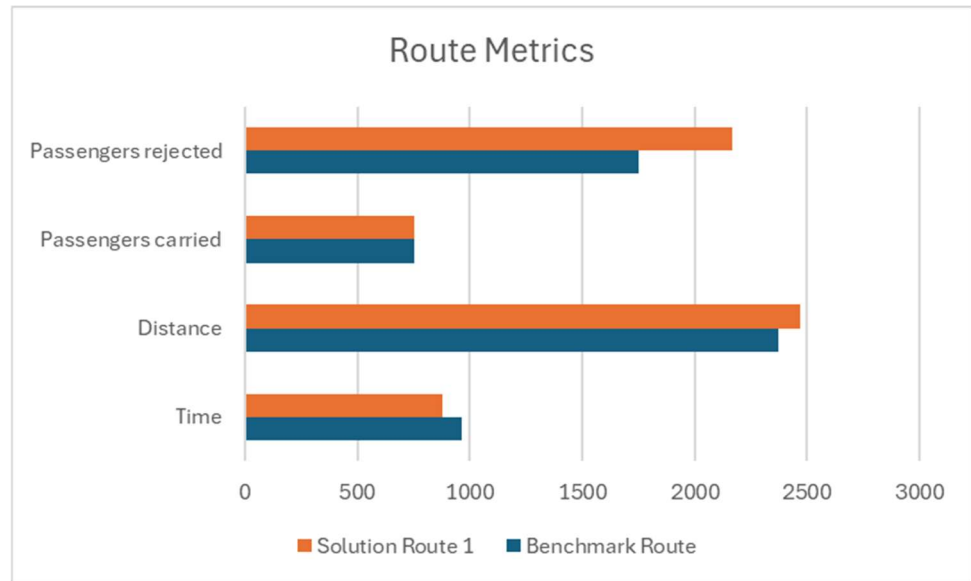


Figure 32: Route metrics for Solution of Benchmark Route 7

The solution route carries slightly more passengers than the benchmark - 755 compared with 753 - but rejects significantly more, with 2,167 passengers unable to board. This increase reflects the fact that the revised routing intersects larger and denser metropolitan markets, most notably the Rhine–Ruhr region (Düsseldorf, Wuppertal, Hagen), Berlin, and the Stettin–Poznań axis, all of which show strong long-distance passenger flows. While this enhances potential ridership, it also exposes the service to more severe capacity strain, pushing rejected demand even higher than in the benchmark configuration. As a result, although the solution route captures additional boardings, it also becomes more sensitive to overloads, indicating that a single long-distance train is insufficient to satisfy the concentrated demand structure of the new alignment.

In financial terms, however, the solution route outperforms the benchmark across nearly all major indicators. Revenue rises substantially to €101,827 - nearly €10,000 more than the benchmark - reflecting the greater number of high-demand nodes integrated into the corridor. Interestingly, operating costs rise only minimally, from €37,245 on the benchmark to €37,170 on the solution route, despite the longer distance and more complex routing. This shows that the changes in infrastructure usage do not significantly increase the cost burden and that the efficiency improvements from faster running sections help offset the added geographic extent. The result is a total operating profit of €64,657, well above the benchmark's €55,308. The profit margin increases accordingly, reaching 63.5 percent for the solution route compared to 59.8 percent for the benchmark. These figures signal that from a commercial standpoint, the solution alignment is more profitable and more attractive.

The performance differences between the two routes underline two contrasting strategic philosophies. The benchmark route offers a balanced long-distance structure that maintains manageable capacity pressures, even though bottlenecks still occur in central Germany and western Poland. It is stable, predictable, and well aligned with existing flows between major German and Polish

population centres. The solution route, by contrast, expands the corridor to incorporate additional high-demand metropolitan regions. This unlocks new sources of revenue and improves profitability, but at the cost of dramatically increasing rejected passengers, particularly in Germany's western conurbation and around Berlin. The heavier demand concentration suggests that - while the solution route is commercially superior - it would require increased capacity provision to be operationally viable in practice.

In conclusion, the solution route demonstrates a significant financial advantage through higher revenue and profit margins, combined with a shorter travel time that improves its competitive positioning. However, these gains are achieved through a corridor design that intensifies capacity strain and produces substantially more rejected passengers. The benchmark route therefore remains more balanced from an operational perspective, while the solution route clearly excels economically. In strategic terms, the solution route is preferable only if additional capacity, either through larger trainsets or increased frequency, can be provided to mitigate the very high levels of unmet demand generated by its expanded market coverage.

6.6.8 Summary of Results for Multi-objective LPP

The comparison of the seven benchmark routes with their corresponding solution routes reveals a diverse set of outcomes shaped by differences in routing structure, capacity distribution, and cost-revenue dynamics. For the first benchmark route, the solution alignment reduced unmet demand and improved travel time while slightly lowering profitability. Although both routes performed well, the benchmark remained marginally more financially efficient. The solver therefore identified the existing corridor as a strong baseline configuration.

For the second route, the solution reintroduced the high-speed Hannover corridor, resulting in shorter travel times and fewer rejected passengers than the benchmark. Revenue increased slightly, but the higher infrastructure costs reduced the profit margin. Overall, the benchmark remained financially superior, although the solution route showed strategic improvements in capacity alignment and speed.

The analysis of Route 3 showed that the solution route matched the benchmark exactly. The solver therefore confirmed that the existing Hamburg–Salzburg corridor is already optimal within current infrastructure and demand constraints. This indicated a stable and efficient long-distance axis requiring no structural modification.

For Route 4, the alternative alignment through the Rhine–Main region produced higher revenue and more transported passengers, but it also generated substantially higher rejected demand and operating costs. Its profit margin remained strong, yet slightly lower than the benchmark. The benchmark proved more balanced, whereas the solution route offered faster travel times at the cost of increased operational strain.

In the case of Route 5, the solution route dramatically expanded the corridor into Belgium and Germany, generating far higher revenue and a larger profit than the benchmark. However, this came with excessive rejected passengers and significantly longer travel times. The benchmark retained a clearer operational focus, while the solution route demonstrated the commercial potential of tapping into multiple metropolitan markets.

For Route 6, the solution route produced higher passenger volumes and greater profit by routing through northern Italy's dense travel markets, though at the cost of increased rejected passengers

and higher complexity. Its profit margin slightly exceeded that of the benchmark, but the operational balance deteriorated. The benchmark remained more coherent, whereas the solution route required greater capacity provision to function effectively.

Finally, Route 7 showed that the solution alignment, which extended the corridor through Düsseldorf, Berlin, Szczecin, and Poznań, achieved the highest profit increase of all evaluated routes. Despite the significantly higher rejected demand caused by dense metropolitan catchment areas, the route delivered very strong revenue and an improved profit margin. The benchmark offered more stability, but the solution route provided superior financial performance, provided capacity could be increased.

Overall, the seven comparisons reveal a consistent pattern: solution routes often boost revenue and financial returns but tend to introduce heavier capacity strain and higher levels of rejected passengers. Benchmark routes generally offer more operational balance, while several solution routes highlight where targeted capacity expansions could unlock substantial commercial gains.

6.7 Cross-comparison of the results for various objectives

The results of the single-objective and multi-objective Line Planning Problems (LPPs) reveal substantial differences in the economic performance, spatial route patterns, and overall network characteristics derived from each modelling approach. The single-objective formulations, which individually minimized travel time or distance and maximized profit, produced a set of highly specialized and extreme solutions. In contrast, the multi-objective LPPs - implemented through a weighted-sum approach and an extended Pareto-based analysis - generated more balanced networks that explicitly capture trade-offs between multiple performance criteria. The following sections outline these differences in detail and highlight how the inclusion of multiple objectives alters the resulting railway line plan.

Economic Performance Differences

The single-objective models demonstrate a clear divergence in economic outcomes depending on the optimized criterion. The travel-time minimization model yields an economically fragile network, producing only marginal profit and in some cases even generating loss-making services. This configuration prioritizes operational speed over financial viability, resulting in a network that provides high service quality at the expense of economic sustainability. In contrast, the distance-minimizing formulation achieves comparatively higher profitability due to its compact route configurations and efficient resource usage. However, the total system scale remains small, reducing the absolute profit despite a high relative profit margin.

The profit-maximizing model stands in stark contrast to the previous two. It produces a network with exceptionally high total revenue and profit, driven by long-distance, demand-rich international corridors. This solution exploits high-volume origin–destination pairs and fills train capacity to levels unattainable in the time- or distance-minimizing scenarios. Yet this strong focus on purely economic criteria comes at the cost of very long travel distances and prolonged running times.

The multi-objective weighted-sum approach produces more moderate results, delivering profit levels that lie between the distance-minimizing and profit-maximizing scenarios. Although the total profit is significantly lower than under pure profit maximization, it exceeds the economically limited outcome of the distance-minimizing solution. Compared to the extremes of the single-objective cases, the weighted-sum model operates at a clearly more balanced point in the objective space. Profit margins remain within an efficient range, but the network avoids excessively long routes,

indicating that moderate weights on time and distance shift the system away from purely profit-driven extremities.

Spatial and Structural Characteristics of the Resulting Networks

The spatial configuration of the lines reveals one of the most pronounced differences between single- and multi-objective LPPs. Both the time- and distance-minimizing models produce networks that are compact and regionally contained. In these cases, the majority of selected routes run through the Rhine–Ruhr region, leveraging its high population density and short inter-city distances. Route lengths are limited, and the number of stops per line remains moderate, following the structural logic of minimizing generalized travel impedance.

In contrast, the profit-maximizing model constructs a network concentrated around two main international axes: one connecting Poland to Western Europe (e.g., Gdańsk–Paris) and another linking Northern Germany to Southern France (e.g., Osnabrück–Marseille/Toulon). These routes are substantially longer and run across multiple countries, exploiting economies of scale and high-value passenger flows. The spatial footprint of this network is thus fundamentally different from the regional structure of the time and distance objectives; here, long-haul connectivity dominates. The multi-objective weighted-sum approach results in a network that resembles the profit-maximizing pattern structurally but contains important modifications. While the same two major international corridors remain, the selected routes shift toward shorter variants. The model tends to avoid the longest and most time-consuming paths chosen under pure profit maximization and instead favours slightly more efficient alternatives with reduced running times and distances. This illustrates that the applied weights, though modest, impose sufficient pressure to steer the solution toward a more operationally efficient layout while maintaining its international orientation and economic strength.

Route-Level Trade-Offs and Adjustments

A more detailed examination of individual routes highlights further distinctions. In the time-minimizing model, the network avoids large numbers of intermediate stops, resulting in relatively short routes designed to keep travel times minimal. The distance-minimizing model produces similarly compact lines but shows stronger financial performance, as route length reductions contribute directly to cost savings. However, both solutions remain limited in spatial reach and do not exploit high-demand long-distance connections.

The multi-objective weighted-sum solution bridges this gap by enabling a partial expansion toward long-distance travel while still limiting the excessive route lengths present in the profit-maximizing scenario. This results in a routemap composed of long but not extreme segments, creating a compromise between economic output and operational efficiency. Some long-haul variants are replaced with shorter alternatives, and total travel time across the network decreases compared to the pure profit solution.

Insights from the Multi-Objective Solutions

The multi-objective analysis further illuminates how the network evolves when the relative importance of objectives is varied. Unlike the weighted-sum model, which provides only a single balance point, the Pareto approach reveals an entire frontier of efficient solutions. Across numerous weight combinations, alternative route alignments emerge for key benchmark origin–destination pairs. These alternatives include longer benchmark-like lines with improved coverage, shorter

variants with better time efficiency, and intermediate designs that sacrifice small portions of profit to achieve noticeable improvements in travel time or distance.

Overall, the Pareto-based results demonstrate that even within profitable corridors, multiple feasible trade-off solutions exist. Depending on stakeholder priorities - whether economic, environmental, or passenger-oriented - the decision-maker can select the most desirable compromise. This flexibility is absent in the single-objective models, which produce only extreme endpoints without illustrating the intermediate trade-offs.

Summary

In summary, the single-objective LPPs generate highly polarized outcomes, optimizing one dimension at the expense of others and producing networks that either maximize operational efficiency or profitability but never both simultaneously. The multi-objective approaches offer a more nuanced and realistic picture. They reveal that long and highly profitable international services remain structurally attractive even under multi-objective trade-offs, but they also show how moderate weighting or alternative balancing points can improve operational metrics without sacrificing the core economic strength of the network. This demonstrates the value of multi-objective optimization in railway line planning, where realistic operational decisions must inherently balance competing performance dimensions rather than optimize a single goal in isolation.

7. Conclusion

This thesis develops and applies a solver-based decision-support framework for the strategic line planning problem in long-distance passenger rail networks, with a particular focus on the Central European context. A geographically grounded railway network is constructed from existing infrastructure, and a comprehensive set of feasible candidate routes is generated between major city pairs. The line planning problem is formulated as a mixed-integer linear program, enabling the systematic evaluation of alternative line configurations under demand, capacity, and operational constraints. Multiple objective functions - covering travel time, travel distance, and economic performance - are analyzed to capture the inherent trade-offs between efficiency and profitability. The framework is applied to a set of real-world benchmark corridors, allowing solver-generated solutions to be compared against existing operated services. Through this approach, the thesis demonstrates how infrastructure-aware optimization can reveal structurally efficient and economically viable long-distance rail services, providing actionable insights for strategic railway planning in large-scale, heterogeneous networks.

With respect to the first research question,

- What is the optimal train line or combination of train lines in Central Europe on existing rail infrastructure, considering different train formations, operational constraints, and demand scenarios?

the results demonstrate that no single “optimal” train line exists independently of the chosen planning objective. Instead, the optimal solution emerges as a set of line configurations whose structure depends strongly on the optimization criterion. The travel-time- and distance-minimizing models favor short, regionally concentrated routes with limited stopping patterns, resulting in compact networks with high operational efficiency but comparatively low economic output. In contrast, the profit-maximizing model consistently selects long-distance, international corridors connecting major metropolitan areas, as these routes combine high passenger volumes with favorable revenue-

to-cost ratios. The multi-objective formulations reconcile these extremes by identifying compromise solutions that retain the core international corridors while shortening routes and reducing unnecessary detours. These results indicate that, under realistic demand and cost assumptions, the most effective line plans in Central Europe are selective combinations of high-demand international services rather than dense all-covering networks.

The second research question,

- How do existing infrastructure limitations (e.g., existing network, passenger spread, capacity constraints) affect the feasibility and performance of different train line configurations on the Central European Network?

concerned the impact of infrastructure limitations on feasibility and performance. The findings clearly show that existing network heterogeneity is the dominant constraint shaping feasible line plans. Capacity bottlenecks, uneven speed profiles, and the shared use of infrastructure by high-speed, regional, and freight services significantly restrict the set of implementable routes. Lines traversing fully upgraded high-speed corridors consistently outperform alternatives that rely on mixed or conventional infrastructure, even when demand levels are comparable. Moreover, passenger demand concentration around major hubs amplifies the attractiveness of certain corridors while rendering others structurally inefficient. As a result, infrastructure constraints do not merely limit performance but actively redirect optimal solutions toward corridors where continuity, capacity, and demand align, underscoring the importance of infrastructure-aware line planning.

Regarding the third research question,

- Which mathematical models from existing literature (e.g., nonlinear, mixed-integer, or bi-level models) are most suitable for adapting to the Central European high-speed rail context, and how can they be customized for this specific corridor?

the thesis demonstrates that mixed-integer linear programming (MILP) formulations provide the most suitable modeling framework for the Central European context when extended appropriately. While nonlinear and bi-level models offer conceptual richness, they become computationally prohibitive at continental scale under realistic constraints. By integrating path-based representations, capacity constraints, and explicit revenue and cost formulations, the adopted MILP framework successfully captures both operational feasibility and economic performance. The customization of this model to Central Europe - through the inclusion of real infrastructure topology, cross-border cost components, and demand-driven revenue functions - bridges the gap between abstract line planning theory and applied strategic planning.

Finally, the fourth research question,

- What insights can be derived from applying the selected model to a European corridor that might inform future strategic planning by Deutsche Bahn (DB) and Österreichische Bundesbahnen (ÖBB)?

addressed the strategic insights derived for railway operators such as Deutsche Bahn and Österreichische Bundesbahnen. The results suggest that future competitiveness will depend less on expanding network coverage and more on selectively strengthening high-performing international corridors. Multi-objective analysis reveals that modest sacrifices in profit can yield substantial improvements in travel time and operational efficiency, offering a transparent basis for strategic

trade-off decisions. The developed Decision Support System further enables planners to explore alternative scenarios, evaluate Pareto-efficient solutions, and adapt service concepts to changing demand or policy priorities. Consequently, the thesis provides actionable guidance for long-term line planning by demonstrating how data-driven optimization can support economically viable, operationally feasible, and strategically robust high-speed rail services in Central Europe.

8. Limitations and Future Research Directions

Although the modelling approach and empirical analysis presented in this thesis provide valuable insights into the structure and performance of railway line plans under different objective configurations, several limitations remain. These limitations arise from modelling assumptions, data constraints, computational considerations, and the simplified representation of operational processes. Addressing these issues offers promising directions for future research and further methodological refinement.

Limitations

The demand model applied in this thesis relies on deterministic Origin–Destination matrices that assume fixed passenger volumes independent of the selected line plan. This ignores endogenous demand reactions, such as passengers switching routes or modes in response to changes in travel time, frequency, or service quality. Likewise, peak–off-peak variations, seasonal patterns, and stochastic fluctuations in demand are not represented. As a result, the model may overestimate or underestimate the attractiveness and profitability of certain lines, particularly long-distance international services.

The line planning problem is solved without an explicit timetable or detailed infrastructure capacity model. Although travel times, distances, and certain capacity limitations are included, the model does not incorporate track conflicts, station dwell-time interactions, or timetabling feasibility. In reality, constructing a feasible timetable for long international corridors - especially those spanning countries with heterogeneous signaling systems - may require substantial adjustments to the proposed line plans. The absence of timetable integration thus limits the operational realism of the results.

The model assumes homogeneous rolling stock with fixed operating costs, maximum capacities, and cost structures. In practice, railway operators employ a heterogeneous fleet with varying energy consumption, seat configurations, and maintenance characteristics. Similarly, the cost model is linear and static, whereas real-world cost structures include fixed crew costs, nonlinear maintenance effects, and capacity-dependent cost increments. These simplifications may affect the accuracy of the profitability assessments.

Although this thesis evaluates multiple objectives - profit, travel time, and operated distance - the selected objectives do not encompass the full set of criteria relevant in passenger rail planning. Environmental externalities, accessibility equity, robustness of connections, and political priorities are not explicitly modeled. Furthermore, the weighted-sum approach used in the multi-objective analysis may introduce bias, as the results depend heavily on the numerical weights chosen by the analyst. Certain regions of the true Pareto frontier may remain unexplored due to the well-known limitations of linear scalarization.

While the mixed integer linear programming formulation is computationally tractable, the exploration of alternative configurations - particularly through multi-objective analysis - remains limited by computational resources. Only a subset of all possible weight combinations and candidate line

configurations could be evaluated. Consequently, the full space of efficient solutions is likely underrepresented, and additional non-dominated line plans may exist outside the evaluated scenarios.

Future Research Directions

An important extension of this work is the integration of line planning with feasible timetabling and detailed infrastructure capacity models. Approaches such as synchronous line planning–timetabling optimization, microscopic capacity simulation, or conflict-based track assignment could be employed to ensure that the resulting line plans are operationally implementable. This integration would also allow the evaluation of robustness, delay propagation, and network reliability.

Future research should incorporate elastic demand modeling, where passenger volumes depend on service attributes such as travel time, frequency, fare levels, and reliability. Combining the LPP with discrete choice models or stochastic demand estimation would enable a more accurate assessment of economic performance. Additionally, introducing demand uncertainty or scenario-based demand forecasts could improve the robustness of the resulting line plans.

To enhance policy relevance, future work could expand the objective space to include environmental impacts (e.g., CO₂ emissions, energy consumption), social objectives (e.g., regional accessibility, equity), and operational robustness. Multi-criteria decision analysis could then be employed to reflect diverse stakeholder interests. Nonlinear or ϵ -constraint-based multi-objective optimization methods may help overcome the limitations of weighted-sum scalarization and reveal a more complete Pareto frontier.

Incorporating rolling stock assignment into the line planning model would allow researchers to analyze the interaction between line structure, vehicle availability, and cost efficiency. This could involve heterogeneous fleet types, variable train lengths, maintenance requirements, and dynamic energy pricing. More sophisticated cost models could also reflect economies of scale, crew scheduling constraints, and depot locations.

Another direction is the development of dynamic or real-time line planning frameworks that adapt to changing demand patterns, disruptions, or operational incidents. Methods combining reinforcement learning, simulation-based optimization, or rolling-horizon planning may offer tools to update line plans more flexibly. Such approaches would be particularly relevant for international networks exposed to varying cross-border demand or disruptions.

Finally, future research may explore extended geographical coverage beyond the network used in this thesis. Including additional countries or corridors would allow the analysis of trans-European connectivity, interoperability challenges, and cross-border policy harmonization. Investigating coordination mechanisms between national railway operators could provide insights into how line planning decisions interact on a continental scale.

In summary, while the models developed in this thesis provide a structured and insightful analysis of railway line planning under multiple objectives, several simplifying assumptions limit their direct operational applicability. Future research can build on this work by incorporating greater operational detail, richer demand modeling, broader objective sets, and more comprehensive scenario exploration. These enhancements will further strengthen the usefulness of line planning models as decision-support tools in the context of modern, international rail networks.

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Appendix

```

=== TOTAL ===
Total distance km           1603.2
Total duration min          460.0
Total revenue € (Boarding model) 61945.0
Total passengers carried     747.0
Total rejected passengers    1856.0
Total cost € (per run)       24751.0
Total cost € (all trains)    24751.0
Operating profit €           37194.0
Operating margin %           60.0

```

```

=== PER LEG ===

```

Leg	From	To	Distance (km)	Time (min)	Passengers on leg	Cost leg (€)	Border?
104→105	Wien St.	Pölten	105.2	29.0	268	495	False
105→109	St. Pölten	Linz	166.3	44.0	371	750	False
109→81	Linz	Passau	134.1	57.0	372	954	True
81→80	Passau	Plattling	75.4	25.0	371	1439	False
80→73	Plattling	Regensburg	103.1	29.0	373	1941	False
73→72	Regensburg	Nürnberg	163.4	51.0	373	3056	False
72→71	Nürnberg	Erlangen	35.0	11.0	372	694	False
71→65	Erlangen	Würzburg	168.5	26.0	372	3100	False
65→62	Würzburg	Frankfurt	193.0	28.0	372	3541	False
62→60	Frankfurt	Wiesbaden	66.6	30.0	373	1292	False
60→59	Wiesbaden	Koblenz	146.9	45.0	373	2751	False
59→58	Koblenz	Bonn	91.0	30.0	372	1727	False
58→56	Bonn	Köln	53.7	20.0	372	1044	False
56→55	Köln	Düsseldorf	65.6	22.0	228	1260	False
55→51	Düsseldorf	Duisburg	35.6	13.0	117	708	False

```

=== PER STATION (SUMS) ===

```

Station #	Station	Boardings	Revenue (Boarding €)	Alightings	Onboard (after stop)	Rejected
104	Wien	268	32964	0	268	0
105	St. Pölten	107	13630	4	371	178
109	Linz	13	1474	12	372	252
81	Passau	10	1124	11	371	246
80	Plattling	14	1353	12	373	235
73	Regensburg	15	1246	15	373	219
72	Nürnberg	30	2088	31	372	159
71	Erlangen	21	1304	21	372	178
65	Würzburg	24	1154	24	372	162
62	Frankfurt	66	2524	65	373	42
60	Wiesbaden	39	1312	39	373	83
59	Koblenz	39	679	40	372	77
58	Bonn	60	721	60	372	25
56	Köln	27	273	171	228	0
55	Düsseldorf	14	98	125	117	0
51	Duisburg	0	0	117	0	0

```

=== TOTAL ===
Total distance km           1228.1
Total duration min          478.0
Total revenue € (Boarding model) 52994.0
Total passengers carried     733.0
Total rejected passengers    427.0
Total cost € (per run)       23320.0
Total cost € (all trains)    23320.0
Operating profit €           29674.0
Operating margin %           56.0

=== PER LEG ===
Leg      From      To      Distance (km)  Time (min)  Passengers on leg  Cost leg (€)  Border?
32→33    Berlin    Potsdam    51.4         33.0        166              1027         False
33→34    Potsdam    Magdeburg  188.1        97.0        341              3581         False
34→43    Magdeburg    Halle    139.4        69.0        373              2662         False
43→47    Halle      Erfurt    148.7        27.0        372              2750         False
47→63    Erfurt     Fulda     211.1        38.0        372              3882         False
63→62    Fulda      Frankfurt  135.8        70.0        371              2599         False
62→64    Frankfurt  Darmstadt  48.0         15.0        336              934          False
64→66    Darmstadt  Mannheim   70.3         15.0        365              1331         False
66→67    Mannheim  Heidelberg  32.2         44.0        332              705          False
67→69    Heidelberg  Karlsruhe  82.7         31.0        310              1580         False
69→70    Karlsruhe  Stuttgart  120.5        39.0        218              2269         False

=== PER STATION (SUMS) ===
Station #  Station  Boardings  Revenue (Boarding €)  Alightings  Onboard (after stop)  Rejected
32         Berlin    166         19861                 0            166                  0
33         Potsdam    179         18300                 4            341                  0
34         Magdeburg   52          4262                20            373                 110
43         Halle      25          1577                26            372                 121
47         Erfurt     30          1175                30            372                 101
63         Fulda      29           856                30            371                  94
62         Frankfurt  61          2278                96            336                  0
64         Darmstadt  72          2208                43            365                  0
66         Mannheim   49          1349                82            332                  0
67         Heidelberg 45           867                67            310                  0
69         Karlsruhe  25           262               117            218                  0
70         Stuttgart   0              0               218              0                  0

```

Appendix 2: Solution Benchmark Route 2

=== TOTAL ===								
Total distance km			1398.7					
Total duration min			358.0					
Total revenue € (Boarding model)			50139.0					
Total passengers carried			661.0					
Total rejected passengers			389.0					
Total cost € (per run)			26388.0					
Total cost € (all trains)			26388.0					
Operating profit €			23751.0					
Operating margin %			47.4					
=== PER LEG ===								
Leg	From	To	Distance (km)	Time (min)	Passengers on leg	Cost leg (€)	Border?	
28→37	Hamburg	Hannover	275.1	67.0	168	5076	False	
37→42	Hannover	Göttingen	162.7	41.0	308	3025	False	
42→48	Göttingen	Kassel	71.4	16.0	372	1352	False	
48→63	Kassel	Fulda	102.0	38.0	372	1938	False	
63→65	Fulda	Würzburg	106.1	66.0	371	2063	False	
65→71	Würzburg	Erlangen	168.5	26.0	371	3100	False	
71→72	Erlangen	Nürnberg	35.0	11.0	371	694	False	
72→74	Nürnberg	Ingolstadt	135.6	27.0	351	2516	False	
74→77	Ingolstadt	München	126.0	36.0	354	2362	False	
77→110	München	Salzburg	216.4	30.0	89	4262	True	
=== PER STATION (SUMS) ===								
Station #	Station	Boardings	Revenue (Boarding €)	Alightings	Onboard (after stop)	Rejected		
28	Hamburg	168	18968	0	168	0		
37	Hannover	152	15537	12	308	0		
42	Göttingen	81	6046	17	372	65		
48	Kassel	28	1840	28	372	102		
63	Fulda	26	1553	27	371	95		
65	Würzburg	35	1641	35	371	72		
71	Erlangen	41	1427	41	371	54		
72	Nürnberg	62	2059	82	351	0		
74	Ingolstadt	61	1005	58	354	0		
77	München	7	63	272	89	0		
110	Salzburg	0	0	89	0	0		

Appendix 3: Solution Benchmark Route 3

=== TOTAL ===							
Total distance km			2064.1				
Total duration min			618.0				
Total revenue € (Boarding model)			85081.0				
Total passengers carried			790.0				
Total rejected passengers			1058.0				
Total cost € (per run)			26937.0				
Total cost € (all trains)			26937.0				
Operating profit €			58144.0				
Operating margin %			68.3				
=== PER LEG ===							
Leg	From	To	Distance (km)	Time (min)	Passengers on leg	Cost leg (€)	Border?
12→22	Paris	Marne la Vallee	86.3	59.0	239	1201	False
22→14	Marne la Vallee	Reims	192.3	45.0	371	2455	False
14→23	Reims	Nancy	307.2	90.0	374	3924	False
23→15	Nancy	Straßburg	224.1	62.0	373	2870	False
15→70	Straßburg	Stuttgart	241.4	80.0	372	3412	True
70→75	Stuttgart	Ulm	135.7	42.0	372	2545	False
75→76	Ulm	Augsburg	130.0	40.0	372	2441	False
76→77	Augsburg	München	94.9	29.0	371	1795	False
77→110	München	Salzburg	216.4	30.0	331	4262	True
110→109	Salzburg	Linz	164.3	68.0	359	787	False
109→105	Linz	St. Pölten	166.3	44.0	342	750	False
105→104	St. Pölten	Wien	105.2	29.0	313	495	False
=== PER STATION (SUMS) ===							
Station #	Station	Boardings	Revenue (Boarding €)	Alightings	Onboard (after stop)	Rejected	
12	Paris	239	44522	0	239	0	
22	Marne la Vallee	139	18968	7	371	106	
14	Reims	15	1610	12	374	227	
23	Nancy	14	1306	15	373	212	
15	Straßburg	22	1700	23	372	182	
70	Stuttgart	43	2609	43	372	109	
75	Ulm	29	1512	29	372	133	
76	Augsburg	41	2051	42	371	89	
77	München	66	3696	106	331	0	
110	Salzburg	75	4112	47	359	0	
109	Linz	57	2144	74	342	0	
105	St. Pölten	50	850	79	313	0	
104	Wien	0	0	313	0	0	

Appendix 4: Solution Benchmark Route 4

```

=== TOTAL ===
Total distance km          1315.1
Total duration min         369.0
Total revenue € (Boarding model) 41798.0
Total passengers carried   486.0
Total rejected passengers   0.0
Total cost € (per run)     16906.0
Total cost € (all trains)  16906.0
Operating profit €         24892.0
Operating margin %         59.6

=== PER LEG ===
  Leg      From      To  Distance (km)  Time (min)  Passengers on leg  Cost leg (€)  Border?
12→22      Paris Marne la Vallee      86.3      59.0      112      1201      False
22→21 Marne la Vallee      Dijon      409.3      92.0      214      5160      False
21→11      Dijon      Lyon      284.3      82.0      287      3633      False
11→20      Lyon      Valence      161.0      23.0      279      2036      False
20→19      Valence      Avignon      172.7      83.0      288      2288      False
19→18      Avignon Aix en Provence      151.9      20.0      270      1920      False
18→10 Aix en Provence      Marseille      49.6      10.0      230      667      False

=== PER STATION (SUMS) ===
  Station #  Station  Boardings  Revenue (Boarding €)  Alightings  Onboard (after stop)  Rejected
      12      Paris      112      16457      0      112      0
      22 Marne la Vallee      109      11046      7      214      0
      21      Dijon      92      6772      19      287      0
      11      Lyon      51      3032      59      279      0
      20      Valence      51      2844      42      288      0
      19      Avignon      40      1368      58      270      0
      18 Aix en Provence      31      279      71      230      0
      10      Marseille      0      0      230      0      0

```

Appendix 5: Solution Benchmark Route 5

=== TOTAL ===							
Total distance km			1850.6				
Total duration min			1074.0				
Total revenue € (Boarding model)			49161.0				
Total passengers carried			687.0				
Total rejected passengers			273.0				
Total cost € (per run)			20262.0				
Total cost € (all trains)			20262.0				
Operating profit €			28899.0				
Operating margin %			58.8				
=== PER LEG ===							
Leg	From	To	Distance (km)	Time (min)	Passengers on leg	Cost leg (€)	Border?
10→17	Marseille	Toulon	92.4	40.0	153	1240	False
17→16	Toulon	Frejus	124.7	48.0	334	1644	False
16→7	Frejus	Nizza	92.6	56.0	371	1272	False
7→1	Nizza	Turin	288.2	304.0	372	4391	True
1→3	Turin	Mailand	209.8	45.0	372	1473	False
3→4	Mailand	Venedig	391.4	134.0	329	3097	True
4→8	Venedig	Udine	175.8	94.0	331	2159	True
8→89	Udine	Ljubliana	270.7	224.0	320	2493	True
89→90	Ljubliana	Zagreb	204.9	129.0	236	2494	True
=== PER STATION (SUMS) ===							
Station #	Station	Boardings	Revenue (Boarding €)	Alightings	Onboard (after stop)	Rejected	
10	Marseille	153	15077	0	153	0	
17	Toulon	185	15721	4	334	0	
16	Frejus	49	3211	12	371	128	
7	Nizza	28	1811	27	372	116	
1	Turin	68	4169	68	372	30	
3	Mailand	67	4471	110	329	0	
4	Venedig	58	2357	56	331	0	
8	Udine	51	1811	62	320	0	
89	Ljubliana	28	532	112	236	0	
90	Zagreb	0	0	236	0	0	

Appendix 6: Solution Benchmark Route 6

```

=== TOTAL ===
Total distance km          2371.7
Total duration min         964.0
Total revenue € (Boarding model) 92553.0
Total passengers carried   753.0
Total rejected passengers  1753.0
Total cost € (per run)     37245.0
Total cost € (all trains)  37245.0
Operating profit €        55308.0
Operating margin %        59.8

=== PER LEG ===
Leg      From      To      Distance (km)  Time (min)  Passengers on leg  Cost leg (€)  Border?
86→87    Amsterdam  Utrecht    64.4        27.0        259           699        False
87→88      Utrecht   Arnheim    92.7        32.0        370           971        False
88→51     Arnheim   Duisburg   159.5       30.0        370          1889         True
51→52     Duisburg   Essen     31.8        30.0        372           673        False
52→50      Essen    Bochum     24.4        30.0        372           541        False
50→53      Bochum    Hagen     47.8        30.0        372           958        False
53→49      Hagen     Hamm       77.6        28.0        372          1485        False
49→41      Hamm    Paderborn  128.8       38.0        372          2415        False
41→42     Paderborn Göttingen  184.3       81.0        373          3484        False
42→43     Göttingen Halle     300.3      119.0        372          5621        False
43→44      Halle    Leipzig    55.6        26.0        372          1089        False
44→45     Leipzig   Dresden   171.4       93.0        371          3276        False
45→98     Dresden   Wroclaw   398.7      187.0        348          7801         True
98→99     Wroclaw   Warszawa  634.3      213.0        255          6343        False

=== PER STATION (SUMS) ===
Station #   Station  Boardings  Revenue (Boarding €)  Alightings  Onboard (after stop)
86  Amsterdam    259          36615           0           259
87   Utrecht    120          16520           9           370
88   Arnheim     9           1141           9           370
51  Duisburg     25           3219          23           372
52    Essen     30           4531          30           372
50    Bochum     22           3406          22           372
53    Hagen      18           2766          18           372
49    Hamm       18           2814          18           372          169
41 Paderborn     22           2864          21           373          154
42 Göttingen     24           2660          25           372          140
43    Halle      37           3144          37           372          100
44    Leipzig     70           5891          71           371           23
45    Dresden     65           5248          88           348            0
98   Wroclaw     34           1734         127           255            0
99   Warszawa     0              0         255            0            0

```

Appendix 7: Solution Benchmark Route 7

```
[INFO] Excel matrices loaded: Passenger, Distance, Time, Price
[INFO] Cities successfully assigned to countries.
[INFO] Generating global solver routes (K-shortest paths) ...
```

```
Generated 42988 possible routes (≤ 1100 min).
```

```
[INFO] Global solver routes generated: 42988
[INFO] Starting optimization in Solver mode ...
[INFO] Solver status: Optimal
[INFO] Objective: 1,004.00
```

```
--- Results (Optimization - Solver) ---
```

```
Status: Optimal
Objective value: 1004.0
Active routes: 7 of 42988
```

```
--- Simulation: each active route ---
```

```
--- Simulation: each active route ---
```

```
Route 13143 | Hamm → Hagen → Wuppertal → Düsseldorf → Köln → Bonn → Aachen → Lüttich
```

```
Travel time (one trip): 140 min | Distance: 520 km
```

```
Frequency: 1 runs
```

Station	Board	Alight	Onboard	Revenue €
Hamm	142	0	142	6338.09
Hagen	123	11	254	10109.09
Wuppertal	99	29	324	12360.09
Düsseldorf	63	75	312	13399.09
Köln	23	167	168	13905.09
Bonn	21	63	126	14382.09
Aachen	10	61	75	14682.09
Lüttich	0	75	0	14682.09

```
Revenue per run: 14,682 €
```

```
Cost per run: 10,191 €
```

```
Total revenue: 14,682 €
```

```
Total cost: 10,191 €
```

```
Total profit: 4,491 €
```

Route 23788 | Lüttich → Aachen → Bonn → Köln → Düsseldorf → Wuppertal → Hagen → Hamm
Travel time (one trip): 140 min | Distance: 520 km

Frequency: 1 runs

Station	Board	Alight	Onboard	Revenue €
Lüttich	132	0	132	6510.95
Aachen	120	10	242	9282.40
Bonn	100	28	314	11102.96
Köln	36	132	218	11847.72
Düsseldorf	25	89	154	12382.49
Wuppertal	17	62	109	12692.15
Hagen	8	58	59	12823.31
Hamm	0	59	0	12823.31

Revenue per run: 12,823 €

Cost per run: 9,497 €

Total revenue: 12,823 €

Total cost: 9,497 €

Total profit: 3,326 €

Route 28005 | Saarbrücken → Mannheim → Darmstadt → Frankfurt → Würzburg → Erlangen → Nürnberg → Ulm
Travel time (one trip): 145 min | Distance: 959 km

Frequency: 1 runs

Station	Board	Alight	Onboard	Revenue €
Saarbrücken	114	0	114	4470.00
Mannheim	90	15	189	7163.00
Darmstadt	87	17	259	9456.50
Frankfurt	44	105	198	11176.50
Würzburg	40	35	203	12145.50
Erlangen	30	48	185	12496.50
Nürnberg	8	125	68	12568.50
Ulm	0	68	0	12568.50

Revenue per run: 12,568 €

Cost per run: 17,708 €

Total revenue: 12,568 €

Total cost: 17,708 €

Total profit: -5,140 €

Route 40106 | Ingolstadt → Nürnberg → Erlangen → Würzburg → Frankfurt → Darmstadt → Mannheim → Saarbrücken
Travel time (one trip): 142 min | Distance: 838 km

Frequency: 1 runs

Station	Board	Alight	Onboard	Revenue €
Ingolstadt	118	0	118	6617.36
Nürnberg	84	21	181	9998.36
Erlangen	85	16	250	12871.36
Würzburg	72	27	295	14380.36
Frankfurt	26	145	176	14992.86
Darmstadt	25	46	155	15445.36
Mannheim	9	91	73	15638.86
Saarbrücken	0	73	0	15638.86

Revenue per run: 15,639 €

Cost per run: 15,549 €

Total revenue: 15,639 €

Total cost: 15,549 €

Total profit: 90 €

Route 40795 | Ulm → Nürnberg → Erlangen → Würzburg → Frankfurt → Darmstadt → Mannheim → Saarbrücken
Travel time (one trip): 145 min | Distance: 959 km

Frequency: 1 runs

Station	Board	A light	Onboard	Revenue €
Ulm	116	0	116	4437.00
Nürnberg	84	21	179	7818.00
Erlangen	85	16	248	10691.00
Würzburg	72	27	293	12200.00
Frankfurt	26	145	174	12812.50
Darmstadt	25	45	154	13265.00
Mannheim	9	91	72	13458.50
Saarbrücken	0	72	0	13458.50

Revenue per run: 13,458 €

Cost per run: 17,708 €

Total revenue: 13,458 €

Total cost: 17,708 €

Total profit: -4,250 €

Route 41648 | Saarbrücken → Mannheim → Darmstadt → Frankfurt → Würzburg → Erlangen → Nürnberg → Ingolstadt
Travel time (one trip): 142 min | Distance: 838 km

Frequency: 1 runs

Station	Board	A light	Onboard	Revenue €
Saarbrücken	115	0	115	4739.39
Mannheim	91	15	191	7695.78
Darmstadt	88	17	262	10226.13
Frankfurt	44	105	201	12131.48
Würzburg	40	35	206	13268.98
Erlangen	30	48	188	13771.63
Nürnberg	8	125	71	13978.43
Ingolstadt	0	71	0	13978.43

Revenue per run: 13,978 €

Cost per run: 15,549 €

Total revenue: 13,978 €

Total cost: 15,549 €

Total profit: -1,570 €

Route 41995 | Aachen → Bonn → Köln → Düsseldorf → Wuppertal → Hagen → Hamm → Münster
Travel time (one trip): 150 min | Distance: 497 km

Frequency: 1 runs

Station	Board	Alight	Onboard	Revenue €
Aachen	136	0	136	3968.09
Bonn	115	14	237	6805.50
Köln	47	87	197	8218.95
Düsseldorf	37	63	171	9399.19
Wuppertal	31	47	155	10314.91
Hagen	22	46	131	10905.13
Hamm	15	49	97	11151.06
Münster	0	97	0	11151.06

Revenue per run: 11,151 €

Cost per run: 9,491 €

Total revenue: 11,151 €

Total cost: 9,491 €

Total profit: 1,660 €

--- Totals ---

Total revenue: 94,300.74 €

Total cost: 95,692.81 €

Total profit: -1,392.07 €

[INFO] Drawing geographic network ...

[INFO] Loading rail network from GPKG ...

[INFO] Rail network graph built.

Process finished with exit code 0

Appendix 8: Solution Objective Function 1

```
[INFO] Starting Line Planning Solver ...
[INFO] Loading network parameters from Excel ...
[INFO] Excel matrices loaded: Passenger, Distance, Time, Price
[INFO] Cities successfully assigned to countries.
[INFO] Generating global solver routes (K-shortest paths) ...
```

Generated 42988 possible routes (≤ 1100 min).

```
[INFO] Global solver routes generated: 42988
[INFO] Starting optimization in Solver mode ...
[INFO] Solver status: Optimal
[INFO] Objective: 2,404.53
```

--- Results (Optimization - Solver) ---

```
Status: Optimal
Objective value: 2404.53
Active routes: 7 of 42988
```

--- Simulation: each active route ---

Route 38 | Münster → Hamm → Hagen → Wuppertal → Düsseldorf → Duisburg → Essen → Bochum

Travel time (one trip): 161 min | Distance: 313 km

Frequency: 1 runs

Station	Board	Alight	Onboard	Revenue €
Münster	111	0	111	5554.93
Hamm	116	7	220	9741.34
Hagen	97	21	296	11847.25
Wuppertal	76	43	329	12976.47
Düsseldorf	44	99	274	13766.47
Duisburg	32	89	217	14448.37
Essen	10	138	89	14612.32
Bochum	0	89	0	14612.32

Revenue per run: 14,612 €

Cost per run: 6,237 €

Total revenue: 14,612 €

Total cost: 6,237 €

Total profit: 8,375 €

Route 740 | Bochum → Essen → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Münster

Travel time (one trip): 161 min | Distance: 313 km

Frequency: 1 runs

Station	Board	Alight	Onboard	Revenue €
Bochum	106	0	106	2691.29
Essen	69	22	153	4740.29
Duisburg	62	31	184	6487.72
Düsseldorf	37	61	160	7667.96
Wuppertal	31	45	146	8583.68
Hagen	22	43	125	9173.90
Hamm	15	46	94	9419.83
Münster	0	94	0	9419.83

Revenue per run: 9,420 €

Cost per run: 6,237 €

Total revenue: 9,420 €

Total cost: 6,237 €

Total profit: 3,183 €

Route 5126 | Bochum → Essen → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn

Travel time (one trip): 169 min | Distance: 384 km

Frequency: 1 runs

Station	Board	Alight	Onboard	Revenue €
Bochum	101	0	101	2567.81
Essen	65	22	144	4486.91
Duisburg	58	31	171	6113.62
Düsseldorf	34	61	144	7254.95
Wuppertal	26	45	125	8076.66
Hagen	17	43	99	8625.38
Hamm	9	46	62	8895.38
Paderborn	0	62	0	8895.38

Revenue per run: 8,895 €

Cost per run: 7,515 €

Total revenue: 8,895 €

Total cost: 7,515 €

Total profit: 1,381 €

Route 5364 | Osnabrück → Münster → Hamm → Hagen → Wuppertal → Düsseldorf → Duisburg → Essen

Travel time (one trip): 168 min | Distance: 373 km

Frequency: 1 runs

Station	Board	Alight	Onboard	Revenue €
Osnabrück	127	0	127	12022.52
Münster	97	15	209	16888.86
Hamm	101	16	294	20583.42
Hagen	83	33	344	22459.80
Wuppertal	63	59	348	23375.88
Düsseldorf	33	126	255	23918.39
Duisburg	20	110	165	24246.29
Essen	0	165	0	24246.29

Revenue per run: 24,246 €

Cost per run: 7,320 €

Total revenue: 24,246 €

Total cost: 7,320 €

Total profit: 16,927 €

Route 10824 | Münster → Hamm → Hagen → Bochum → Essen → Duisburg → Düsseldorf → Wuppertal
Travel time (one trip): 176 min | Distance: 322 km

Frequency: 1 runs

Station	Board	Alight	Onboard	Revenue €
Münster	111	0	111	5554.93
Hamm	116	7	220	9741.35
Hagen	97	21	296	11847.25
Bochum	75	43	328	13440.08
Essen	42	98	272	14254.67
Duisburg	32	89	215	14604.67
Düsseldorf	10	137	88	14709.67
Wuppertal	0	88	0	14709.67

Revenue per run: 14,710 €

Cost per run: 6,426 €

Total revenue: 14,710 €

Total cost: 6,426 €

Total profit: 8,284 €

Route 25485 | Essen → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Münster → Osnabrück
Travel time (one trip): 168 min | Distance: 373 km

Frequency: 1 runs

Station	Board	Alight	Onboard	Revenue €
Essen	78	0	78	3043.14
Duisburg	71	14	135	5794.65
Düsseldorf	46	38	143	7915.98
Wuppertal	40	32	151	9678.29
Hagen	31	34	148	11020.60
Hamm	24	38	134	11871.05
Münster	7	80	61	12226.48
Osnabrück	0	61	0	12226.48

Revenue per run: 12,226 €

Cost per run: 7,320 €

Total revenue: 12,226 €

Total cost: 7,320 €

Total profit: 4,907 €

```

Route 31258 | Wuppertal → Düsseldorf → Duisburg → Essen → Bochum → Hagen → Hamm → Münster
Travel time (one trip): 176 min | Distance: 322 km
Frequency: 1 runs

```

Station	Board	Alight	Onboard	Revenue €
Wuppertal	107	0	107	2044.94
Düsseldorf	71	23	155	3910.19
Duisburg	62	31	186	5989.52
Essen	37	62	161	7387.88
Bochum	31	46	146	8486.34
Hagen	22	43	125	9076.56
Hamm	15	46	94	9322.49
Münster	0	94	0	9322.49

```

Revenue per run: 9,322 €
Cost per run: 6,426 €
Total revenue: 9,322 €
Total cost: 6,426 €
Total profit: 2,897 €

```

```

--- Totals ---
Total revenue: 93,432.45 €
Total cost: 47,479.81 €
Total profit: 45,952.64 €
[INFO] Drawing geographic network ...
[INFO] Loading rail network from GPKG ...
[INFO] Rail network graph built.

Process finished with exit code 0

```

Appendix 9: Solution Objective Function 2

```

[INFO] Starting Line Planning Solver ...
[INFO] Loading network parameters from Excel ...
[INFO] Excel matrices loaded: Passenger, Distance, Time, Price
[INFO] Cities successfully assigned to countries.
[INFO] Generating global solver routes (K-shortest paths) ...
[INFO] Global solver routes generated: 42988
[INFO] Starting optimization in Solver mode ...

Generated 42988 possible routes (≤ 1180 min).
[INFO] Solver status: Optimal
[INFO] Objective: 550,197.95

--- Results (Optimization - Solver) ---
Status: Optimal
Objective value: 550197.95
Active routes: 7 of 42988

--- Simulation: each active route ---

Route 10308 | Gdansk → Poznan → Wroclaw → Dresden → Leipzig → Halle → Erfurt → Fulda → Frankfurt → Darmstadt → Mannheim → Saarbrücken → Reims → Marne la Vallee → Paris
Travel time (one trip): 925 min | Distance: 2870 km
Frequency: 1 runs

```

Station	Board	Alight	Onboard	Revenue €
Gdansk	296	0	296	61549.74
Poznan	98	14	372	69607.09
Wroclaw	37	37	372	71724.00
Dresden	62	62	372	74565.12
Leipzig	83	83	372	78727.94
Halle	46	46	372	80673.94
Erfurt	60	60	372	82107.94
Fulda	51	51	372	82814.44
Frankfurt	106	169	309	93146.94
Darmstadt	113	54	368	104059.44
Mannheim	77	73	372	111326.94
Saarbrücken	46	46	372	114702.94
Reims	66	67	371	119202.94
Marne la Vallee	41	115	297	121334.94
Paris	0	297	0	121334.94

```

Revenue per run: 121,335 €
Cost per run: 42,505 €
Total revenue: 121,335 €
Total cost: 42,505 €
Total profit: 78,830 €

Route 17231 | Osnabrück → Münster → Hamm → Hagen → Wuppertal → Köln → Aachen → Lüttich → Reims → Dijon → Lyon → Valence → Avignon → Aix en Provence → Marseille → Toulon
Travel time (one trip): 781 min | Distance: 2375 km
Frequency: 1 runs

```

Station	Board	Alight	Onboard	Revenue €
Osnabrück	300	0	300	56917.16
Münster	87	15	372	61617.12
Hamm	16	16	372	61931.94
Hagen	33	33	372	62610.94
Wuppertal	49	49	372	63580.44
Köln	150	150	372	86581.95
Aachen	40	40	372	90503.20
Lüttich	33	33	372	94050.45
Reims	45	45	372	98051.90
Dijon	69	69	372	102640.55
Lyon	60	118	314	106429.55
Valence	60	67	307	109921.55
Avignon	47	73	281	111622.55
Aix en Provence	37	77	241	112018.55
Marseille	4	188	57	112054.55
Toulon	0	57	0	112054.55

```

Revenue per run: 112,055 €
Cost per run: 33,250 €
Total revenue: 112,055 €
Total cost: 33,250 €
Total profit: 78,805 €

Route 21441 | Osnabrück → Münster → Hamm → Hagen → Wuppertal → Köln → Aachen → Lüttich → Brüssel → Reims → Dijon → Lyon → Valence → Avignon → Aix en Provence → Marseille
Travel time (one trip): 741 min | Distance: 2356 km
Frequency: 1 runs

```

Station	Board	Alight	Onboard	Revenue €
Osnabrück	332	0	332	58588.97
Münster	55	15	372	61096.65
Hamm	16	16	372	61411.47
Hagen	33	33	372	62090.47
Wuppertal	49	49	372	63059.97
Köln	132	132	372	77364.52
Aachen	28	28	372	78483.52
Lüttich	31	31	372	78964.02
Brüssel	129	129	372	98761.02
Reims	33	33	372	101501.27
Dijon	57	57	372	104855.72
Lyon	50	123	299	107813.72
Valence	51	75	275	110657.72
Avignon	39	69	245	111998.72
Aix en Provence	30	78	197	112268.72
Marseille	0	197	0	112268.72

```

Revenue per run: 112,269 €
Cost per run: 32,740 €
Total revenue: 112,269 €
Total cost: 32,740 €
Total profit: 79,528 €

```

Route 32028 Osnabrück → Münster → Hamm → Hagen → Wuppertal → Düsseldorf → Köln → Aachen → Lüttich → Reims → Dijon → Lyon → Valence → Avignon → Aix en Provence → Marseille				
Travel time (one trip): 741 min Distance: 2320 km				
Frequency: 1 runs				
Station	Board	Alight	Onboard	Revenue €
Osnabrück	308	0	308	54498.41
Münster	79	15	372	58297.06
Hamm	16	16	372	58611.88
Hagen	33	33	372	59157.88
Wuppertal	49	49	372	59854.38
Düsseldorf	93	93	372	65669.12
Köln	131	131	372	84436.48
Aachen	29	29	372	86737.48
Lüttich	41	41	372	91450.73
Reims	58	58	372	97167.23
Dijon	82	82	372	103092.93
Lyon	50	130	292	106050.93
Valence	51	67	276	108894.93
Avignon	39	85	230	110235.93
Aix en Provence	30	59	201	110505.93
Marseille	0	201	0	110505.93
Revenue per run: 110,506 €				
Cost per run: 32,726 €				
Total revenue: 110,506 €				
Total cost: 32,726 €				
Total profit: 77,780 €				
Route 33945 Gdansk → Poznan → Wroclaw → Dresden → Leipzig → Halle → Jena → Erfurt → Fulda → Frankfurt → Darmstadt → Mannheim → Saarbrücken → Reims → Marne la Vallee → Paris				
Travel time (one trip): 954 min Distance: 2938 km				
Frequency: 1 runs				
Station	Board	Alight	Onboard	Revenue €
Gdansk	309	0	309	63617.14
Poznan	77	14	372	69956.25
Wroclaw	37	37	372	72073.16
Dresden	62	62	372	74603.81
Leipzig	83	83	372	78361.95
Halle	46	46	372	80031.95
Jena	37	37	372	81136.92
Erfurt	57	57	372	82449.42
Fulda	60	60	372	83421.42
Frankfurt	106	170	308	93753.92
Darmstadt	113	54	367	104666.42
Mannheim	77	72	372	111933.92
Saarbrücken	46	46	372	115309.92
Reims	66	67	371	119809.92
Marne la Vallee	41	115	297	121941.92
Paris	0	297	0	121941.92
Revenue per run: 121,942 €				
Cost per run: 43,817 €				
Total revenue: 121,942 €				
Total cost: 43,817 €				
Total profit: 78,125 €				
Route 34429 Gdansk → Poznan → Wroclaw → Dresden → Leipzig → Jena → Erfurt → Fulda → Frankfurt → Darmstadt → Mannheim → Saarbrücken → Reims → Marne la Vallee → Paris				
Travel time (one trip): 954 min Distance: 2895 km				
Frequency: 1 runs				
Station	Board	Alight	Onboard	Revenue €
Gdansk	295	0	295	61496.13
Poznan	91	14	372	69642.35
Wroclaw	37	37	372	71759.26
Dresden	62	62	372	74627.81
Leipzig	83	83	372	78808.27
Jena	41	41	372	80060.48
Erfurt	61	61	372	81542.98
Fulda	52	52	372	82278.98
Frankfurt	106	166	312	92611.48
Darmstadt	113	54	371	103523.98
Mannheim	77	76	372	110791.48
Saarbrücken	46	46	372	114167.48
Reims	66	67	371	118667.48
Marne la Vallee	41	115	297	120799.48
Paris	0	297	0	120799.48
Revenue per run: 120,799 €				
Cost per run: 43,000 €				
Total revenue: 120,799 €				
Total cost: 43,000 €				
Total profit: 77,799 €				

```

Route 34548 | Osnabrück → Münster → Hamm → Hagen → Wuppertal → Köln → Aachen → Lüttich → Reims → Dijon → Lyon → Valence → Avignon → Aix en Provence → Marseille
Travel time (one trip): 741 min | Distance: 2283 km
Frequency: 1 runs

```

Station	Board	Alight	Onboard	Revenue €
Osnabrück	281	0	281	51675.15
Münster	106	15	372	58487.63
Hamm	16	16	372	58802.45
Hagen	33	33	372	59481.45
Wuppertal	49	49	372	60450.95
Köln	150	150	372	83452.45
Aachen	40	40	372	87373.70
Lüttich	43	43	372	92378.45
Reims	54	54	372	97548.55
Dijon	69	69	372	102137.20
Lyon	50	128	294	105095.20
Valence	51	67	278	107939.20
Avignon	39	82	235	109280.20
Aix en Provence	30	77	188	109550.20
Marseille	0	188	0	109550.20

```

Revenue per run: 109,550 €
Cost per run: 32,010 €
Total revenue: 109,550 €
Total cost: 32,010 €
Total profit: 77,540 €

--- Totals ---
Total revenue: 808,455.74 €
Total cost: 260,048.13 €
Total profit: 548,407.61 €
[INFO] Drawing geographic network ...
[INFO] Loading rail network from GPKG ...
[INFO] Rail network graph built.

Process finished with exit code 0

```

Appendix 10: Solution Objective Function 3

```

[INFO] Starting Line Planning Solver ...
[INFO] Loading network parameters from Excel ...
[INFO] Excel matrices loaded: Passenger, Distance, Time, Price
[INFO] Cities successfully assigned to countries.
[INFO] Generating global solver routes (K-shortest paths) ...
[INFO] Global solver routes generated: 72546
[INFO] Starting multi-objective optimization (Weighted Sum) ...

Generated 72546 possible routes (≤ 1100 min).
[INFO] MO solver status: Optimal

--- Results (Optimization - SolverMO) ---
Status: Optimal
Objective (weighted sum): -139842.45
[INFO] MO objective (weighted sum): -139,842.45
Active routes: 7

--- Simulation of active routes ---

Route 7174: Frejus → Toulon → Marseille → Aix en Provence → Avignon → Valence → Lyon → Dijon → Reims → Brüssel → Lüttich → Aachen → Köln → Düsseldorf → Duisburg → Essen
Time: 747 min | Distance: 2372 km | Frequency: 1

```

Station	Board	Alight	Onboard	Revenue €
Frejus	41	0	41	7172.89
Toulon	38	1	78	14059.03
Marseille	26	8	96	19657.06
Aix en Provence	33	2	127	26099.99
Avignon	32	3	156	31651.92
Valence	33	4	185	36650.05
Lyon	27	11	201	40705.88
Dijon	30	7	224	44446.46
Reims	26	9	241	46230.04
Brüssel	10	54	197	46636.33
Lüttich	15	17	195	47386.51
Aachen	14	19	190	47722.70
Köln	5	71	124	47811.49
Düsseldorf	4	45	83	47872.28
Duisburg	2	36	49	47905.07
Essen	0	49	0	47905.07

```

Total revenue: 47,905 €
Total cost: 32,134 €
Total profit: 15,771 €

Route 28842: Osnabrück → Münster → Hamm → Hagen → Wuppertal → Köln → Aachen → Lüttich → Reims → Dijon → Lyon → Valence → Avignon → Aix en Provence → Marseille → Toulon
Time: 781 min | Distance: 2376 km | Frequency: 1

```

Station	Board	Alight	Onboard	Revenue €
Osnabrück	35	0	35	6725.74
Münster	36	2	69	13321.83
Hamm	31	2	98	18371.81
Hagen	30	3	125	22986.85
Wuppertal	30	8	147	27923.53
Köln	30	29	148	33431.66
Aachen	20	6	162	37170.20
Lüttich	19	7	174	40658.35
Reims	15	8	181	42721.95
Dijon	11	15	177	43606.10
Lyon	6	33	150	44014.70
Valence	7	19	138	44419.70
Avignon	6	23	121	44635.70
Aix en Provence	5	26	100	44689.70
Marseille	0	73	27	44689.70
Toulon	0	27	0	44689.70

```

Total revenue: 44,690 €
Total cost: 33,250 €
Total profit: 11,440 €

Route 31654: Utrecht → Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn → Göttingen → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan
Time: 859 min | Distance: 2407 km | Frequency: 1

```

Station	Board	Alight	Onboard	Revenue €
Utrecht	40	0	40	6419.17
Arnheim	40	1	79	12684.54
Duisburg	35	4	110	18116.91
Düsseldorf	33	8	135	23304.28
Wuppertal	32	6	161	28709.69
Hagen	31	5	187	34135.45
Hamm	28	6	209	38844.69
Paderborn	25	7	227	42544.74
Göttingen	24	8	243	45494.79
Braunschweig	22	15	250	48168.69
Magdeburg	20	17	253	50121.54
Potsdam	19	16	256	51603.04
Berlin	7	89	174	52275.54
Stettin	8	32	150	52893.54
Poznan	4	46	108	53097.54
Warszawa	0	108	0	53097.54

```

Total revenue: 53,098 €
Total cost: 36,553 €
Total profit: 16,545 €

```

Route 34837: Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn → Bielefeld → Hannover → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan					
Time: 829 min Distance: 2296 km Frequency: 1					
Station	Board	Alight	Onboard	Revenue €	
Arnheim	44	0	44	6754.82	
Duisburg	38	2	80	12499.85	
Düsseldorf	36	5	111	17978.88	
Wuppertal	36	4	143	23722.85	
Hagen	35	4	174	29445.16	
Hamm	32	5	201	34305.37	
Paderborn	29	6	224	38311.92	
Bielefeld	25	14	235	41814.86	
Hannover	21	21	235	44404.30	
Braunschweig	22	14	243	47078.20	
Magdeburg	20	16	247	49031.05	
Potsdam	19	15	251	50512.55	
Berlin	7	87	171	51185.05	
Stettin	8	31	148	51803.05	
Poznan	4	45	107	52007.05	
Warszawa	0	107	0	52007.05	
Total revenue: 52,007 €					
Total cost: 35,310 €					
Total profit: 16,697 €					

Route 41270: Nizza → Frejus → Toulon → Marseille → Aix en Provence → Avignon → Valence → Lyon → Dijon → Reims → Brüssel → Lüttich → Aachen → Köln → Düsseldorf → Duisburg					
Time: 773 min Distance: 2433 km Frequency: 1					
Station	Board	Alight	Onboard	Revenue €	
Nizza	35	0	35	5731.09	
Frejus	37	0	72	11956.22	
Toulon	34	2	104	17808.59	
Marseille	23	11	116	22630.39	
Aix en Provence	29	3	142	28074.34	
Avignon	28	4	166	32735.29	
Valence	29	5	190	36950.44	
Lyon	23	13	200	40267.69	
Dijon	26	8	218	43384.69	
Reims	22	11	229	44796.69	
Brüssel	8	60	177	45094.19	
Lüttich	12	19	170	45634.69	
Aachen	11	21	160	45837.69	
Köln	3	77	86	45865.69	
Düsseldorf	2	49	39	45879.69	
Duisburg	0	39	0	45879.69	
Total revenue: 45,880 €					
Total cost: 32,733 €					
Total profit: 13,147 €					

Route 44705: Amsterdam → Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Paderborn → Göttingen → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Pozna					
Time: 879 min Distance: 2469 km Frequency: 1					
Station	Board	Alight	Onboard	Revenue €	
Amsterdam	34	0	34	6111.53	
Arnheim	40	0	74	12376.90	
Duisburg	35	3	106	17809.27	
Düsseldorf	33	7	132	22996.64	
Wuppertal	32	5	159	28402.05	
Hagen	31	5	185	33827.81	
Hamm	28	6	207	38537.05	
Paderborn	25	7	225	42237.10	
Göttingen	24	8	241	45187.15	
Braunschweig	22	15	248	47861.05	
Magdeburg	20	17	251	49813.90	
Potsdam	19	16	254	51295.40	
Berlin	7	88	173	51967.90	
Stettin	8	32	149	52585.90	
Poznan	4	46	107	52789.90	
Warszawa	0	107	0	52789.90	
Total revenue: 52,790 €					
Total cost: 37,170 €					
Total profit: 15,620 €					

Route 54094: Arnheim → Duisburg → Düsseldorf → Wuppertal → Hagen → Hamm → Münster → Bielefeld → Hannover → Braunschweig → Magdeburg → Potsdam → Berlin → Stettin → Poznan →					
Time: 834 min Distance: 2281 km Frequency: 1					
Station	Board	Alight	Onboard	Revenue €	
Arnheim	45	0	45	6818.01	
Duisburg	38	2	81	12549.43	
Düsseldorf	36	5	112	18014.86	
Wuppertal	37	4	145	23788.51	
Hagen	36	4	177	29530.00	
Hamm	33	5	205	34473.01	
Münster	28	10	223	39006.93	
Bielefeld	25	13	235	42509.87	
Hannover	21	20	236	45099.31	
Braunschweig	22	14	244	47773.21	
Magdeburg	20	16	248	49726.06	
Potsdam	19	15	252	51207.56	
Berlin	7	86	173	51880.06	
Stettin	8	32	149	52498.06	
Poznan	4	46	107	52702.06	
Warszawa	0	107	0	52702.06	
Total revenue: 52,702 €					
Total cost: 35,055 €					
Total profit: 17,647 €					

Appendix 11: Solution Pareto Optimum fixed weights