An analysis of European intercity bus and rail travel network and impedance

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SHORT SUMMARY

Bus and rail are prominent modes of public transport in Europe for intercity travel. Their modal networks differ substantially in speed, structure and geographic reach, yet are rarely compared systematically at the continental scale. This study constructs a harmonised, service-level intercity network for 134 cities across 30 European countries using timetable data from major intercity rail and coach operators. Generalised travel time and population-weighted accessibility are computed across city pairs, modes and transfer levels. Results show that rail is considerably faster but spatially concentrated in western and central Europe, while bus provides broader coverage across peripheral regions, including the Balkans, Baltics and Iberian cross-border corridors. Rail accessibility saturates around 15 hours of travel time while bus saturates much later at 40 hours. Intermodal transfers generally fare between bus-only and rail-only connections but outperform them in accessibility for more than two transfers, highlighting the critical role of cross-modal coordination in pan-European connectivity.

Keywords: intercity travel, public transport, bus vs rail, generalised travel time, accessibility.

1. INTRODUCTION

European intercity mobility has become an increasingly contested policy domain as rail market liberalisation and the rapid expansion of long-distance coach services have reshaped the competitive landscape across the continent. Despite this transformation, the academic literature has yet to produce a systematic, pan-European characterisation of how bus and rail services compare in terms of their network-wide performance. Much of the existing work approaches intercity connectivity through metrics such as network topology, station coverage, or route kilometres (Chen et al., 2024) which capture the capacity of a system but not its service quality. When passenger-relevant attributes are examined, studies tend to focus on a single mode or a single national market, limiting their transferability and making cross-modal inference difficult (Van Acker et al., 2020).

Research on intercity bus and rail has developed along largely parallel tracks. Studies of rail accessibility tend to position rail as the primary surface mode while treating bus as a supplement or residual category, underrepresenting the substantial role that cross-border coach operators such as FlixBus and BlaBlaCar now play in the Europe-an intercity travel market. Conversely, the literature on long-distance coach deregulation – particularly analyses of market entry following liberalisation in Germany and France – is rich in economic detail but narrowly scoped, rarely extending to network-wide comparisons of travel time performance or spatial reach (Cinic, 2025;

Grimaldi et al., 2017). The handful of studies that do compare modes directly tend to rely on binary connectivity (whether a link exists) or nominal in-vehicle travel time, neither of which adequately captures the full generalised cost faced by travellers, including waiting time, transfer penalties, and schedule coordination. Furthermore, existing intercity accessibility analyses generally do not account for transfer-based reach or decompose accessibility by mode (Adalioğlu, 2025; Moyano et al., 2018), leaving questions about modal substitutability and structural service gaps largely unanswered at the European scale.

This study addresses these gaps by constructing a comprehensive, continent-wide, service-level intercity network for bus and rail across 30 European countries using operator-reported GTFS timetable data. Rather than relying on infrastructure inventories, the analysis compares what each mode offers in practice – in terms of generalised travel time and population-weighted accessibility – to identify where bus and rail complement, compete with, or structurally substitute one another across Europe. It also explores the role of same- and cross-modal transfers in influencing travel time and accessibility.

The core research question of this study is: "How do bus & rail networks compare in service competitiveness in European intercity travel market in terms of travel time?" Specifically, in which regions and corridors do we observe rail–bus parity and substitutability and where there is clear modal dominance?

2. METHODOLOGY

We construct an intercity rail and bus service network for large urban areas of Europe using timetable data. This is followed by a systematic evaluation of modal network and service characteristics, notably travel time and city-level accessibility.

Data collection

The study region includes 134 large cities in 27 European Union (EU) member states plus Norway, Switzerland and the United Kingdom (UK). Cities are defined as per the EU European Commission's (EC) definition of 'Functional Urban Areas' (FUAs) to include the core centre as well as surrounding commuting regions. FUA boundaries and population estimates are obtained from the EC Eurostat data portal and filtered for populations greater than 0.5 million.

The public transit (PT) timetables are obtained in the standard General Transit Feed Specification (GTFS) format. The majority of the GTFS data feeds are downloaded from the crowdsourced Mobility Database as of November 2025, but operator-specific feeds are obtained for some operators from multiple sources. The data are then filtered for 51 train operators and 4 major bus operators (BlaBlaCar, FlixBus, MÁV, National Express) providing services between 2025 and 2026. Next, these timetables are filtered to include routes which have stop(s) within the boundary of at least two FUAs. Notably, bus stops within 400 m of major train stations are merged into intermodal stations to facilitate cross-modal transfers.

Generalised travel time

Next, mode-specific paths between city OD pairs are obtained from the filtered timetables. The path weight is denoted by generalised travel time (GTT), given as a linear combination of several time components pertinent in long-distance travel as:

$$t = t_W + t_{IV} + \beta_T \cdot t_T + \beta_n \cdot n_T \quad (1)$$

Here, t_W is a constant waiting time at the departure station, t_{IV} is the in-vehicle travel time (IVTT), t_T is the sum of scheduled transfer times at each intermediate station, n_T is the number of transfers, β_T is the perceived importance of transfer time relative to IVTT and β_n is a constant transfer penalty for each transfer. Based on the literature on long-distance travel, the parameter values are taken as t_W = 10 minutes, β_T = 1.7 and β_n = 10 minutes (Wardman, 2013; Wardman et al., 2016). For the sake of computational feasibility, only up to 3 same-station transfers are computed and are constrained to a minimum and maximum transfer/connecting time of 5 and 60 minutes, respectively. To consider feasible paths in addition to the shortest paths, ~50.1 million paths are filtered which have a GTT up to 20 minutes longer than that of the shortest path for each combination of city OD pair, mode, transfers and departure period. For each of these combinations, the median values of GTT, IVTT and transfer time are computed for the subsequent analyses.

Spatial accessibility

While generalised travel time (GTT) at the OD pair level offers granular insights into travel costs between specific city pairs, it falls short for broader analytical decision-making in transport planning and policy. Condensing OD-level GTT into a node-level accessibility metric addresses this by summarising the reachable destinations share under practical constraints like maximum GTT thresholds or transfer limits. This enables scalable comparisons across modes, cities, and scenarios that directly inform infrastructure investments or service expansions. In this study, the accessibility, a_i, of a city i is measured as the share of the population, p_j, across the study FUAs, V, that can be reached from it within a specified threshold on maximum GTT, τ, or maximum number of transfers, v, as follows:

$$a_i(\tau) = \sum_{j \in V:\, t_{ij} \leq \tau} \left(\frac{p_j}{\sum_{j \in V} p_j} \right) \quad \forall i \in V \quad (2.1)$$

$$a_i(v) = \sum_{j \in V:\, (n_T)_{ij} \leq v} \left(\frac{p_j}{\sum_{j \in V} p_j} \right) \quad \forall i \in V \quad (2.2)$$

3. RESULTS AND DISCUSSION

Bus and rail intercity network

Figure 1A depicts the network of direct intercity connections derived from GTFS data, revealing a strongly core–periphery structure. Western and Central Europe form a dense, highly meshed backbone with multiple redundant links, whereas Eastern and Southeastern Europe exhibit sparser, more linear connectivity with fewer alternative paths. Major metropolitan hubs like Paris and London are very well connected to nearby and faraway cities. The German urban cluster has a high concentration of both rail and bus links (red edges) and indicates multimodal redundancy and competition. In contrast, modal specialisation is evident in peripheral regions: rail-only connections (green) are prominent in Germany and parts of south-eastern Spain, reflecting stronger rail infrastructure, while bus-only links (blue) dominate large parts of Eastern Europe and the Balkans, suggesting that bus services compensate for weaker or less integrated rail networks.

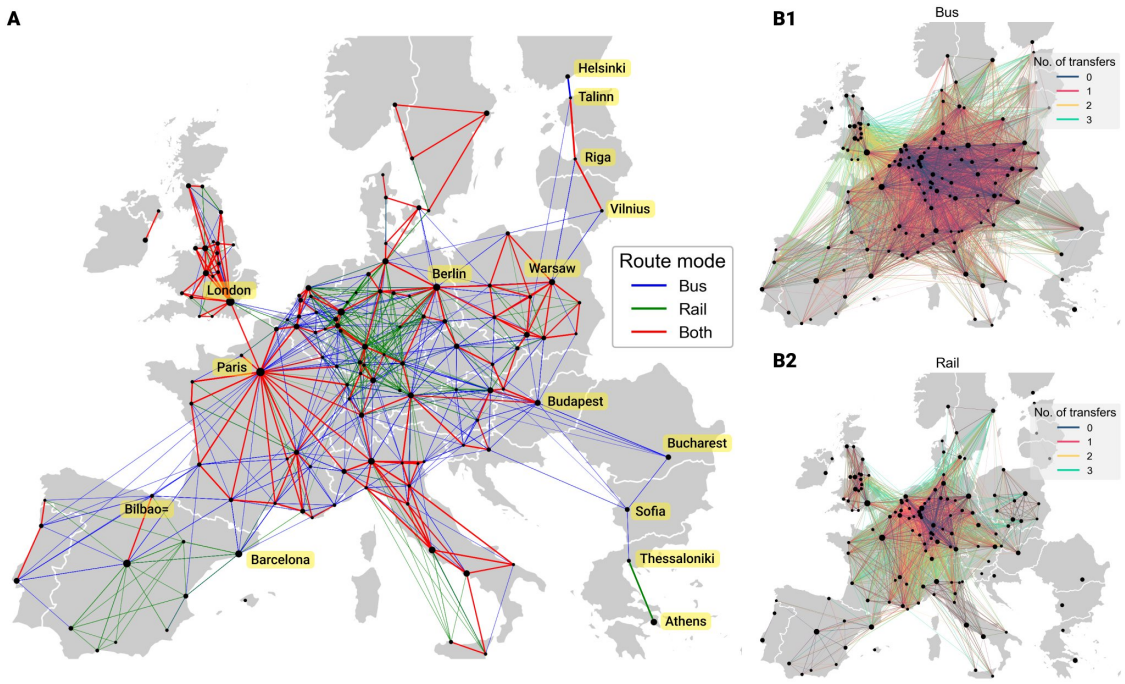


Figure 1: European intercity PT network: (A) Direct routes, labelled with important city names, and (B) modal OD connections with up to 3 transfers by (1) bus and (2) rail.

This spatial imbalance is further reflected in the transfer structure shown in panels B1 and B2. The rail network (B2) is characterised by a higher share of direct (0-transfer) and low-transfer (1-transfer) connections concentrated in Western Europe, especially around Germany, France, the Benelux and the UK. This indicates a relatively efficient, hub-oriented rail system with good long-distance continuity. By contrast, the bus network (B1) is more spatially extensive and uniformly distributed across the continent, enabling connectivity even between distant and peripheral city pairs, albeit often involving more transfers. In effect, buses provide coverage and reach, while rail provides efficiency and directness in the core regions.

Several regional discontinuities stand out. Despite the presence of rail links within the Baltic states (Vilnius–Riga–Tallinn), their integration with the broader European rail network is weak, with Warsaw acting as a key gateway and Helsinki connected primarily via bus–ferry combinations. Similarly, the Iberian Peninsula shows a clear modal asymmetry: northern Spain and Portugal rely heavily on bus connections (e.g., via Bilbao) for cross-border links to France, while rail connectivity is funnelled through a limited number of corridors, notably via Barcelona. In Southeastern Europe, cities such as Budapest, Bucharest, Sofia and Thessaloniki are connected predominantly through bus-based corridors, often requiring multiple transfers, highlighting gaps in high-quality rail integration (Stamos et al., 2016).

Overall, the figure suggests a division of roles between modes: rail dominates in dense, high-demand corridors with strong infrastructure, offering faster and more direct connections, whereas buses play a critical role in ensuring pan-European coverage through a more point-to-point network, particularly in peripheral and lower-density regions where rail networks are less developed or fragmented.

Systematic differences in travel time and reliability across modes

The distributions of median intercity GTT and transfer time across modes and departure periods shown in Figure 2 highlight systematic differences between bus, rail, and intermodal services.

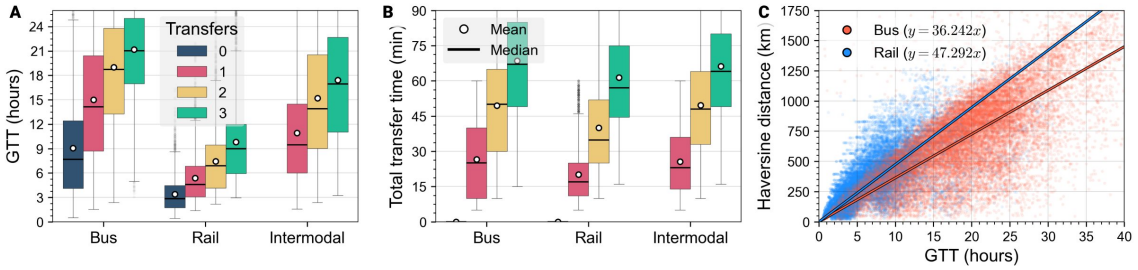


Figure 2: Distribution of path times by mode and transfers: (A) GTT and (B) transfer time. (C) GTT vs intercity Haversine distance by mode.

First, rail consistently outperforms bus in terms of GTT across all transfer levels (panel A). Direct rail journeys cluster around ~3 hours, while direct buses average closer to ~9 hours with substantially greater dispersion. As transfers increase, GTT rises for both modes, but with different patterns: rail exhibits an approximately linear increase, suggesting a relatively constant penalty per transfer, whereas bus shows a concave trend, where the first transfer incurs the largest penalty and subsequent ones add less. This is consistent with a network structure in which early transfers shift passengers onto more efficient corridors, after which additional transfers yield diminishing marginal costs. Further, variability is systematically higher for buses, particularly at higher transfer counts, indicating less predictable travel times and weaker structural constraints on routing. Rail distributions remain comparatively tight, reflecting a more homogeneous and schedule-constrained system.

Panel B isolates total transfer time. As expected, transfer time increases with the number of transfers, but modal differences are less pronounced, partly due to the imposed 60-minute cap per transfer. Still, rail tends to have slightly lower and less dispersed transfer times, indicating better coordination or higher service frequency. Bus transfers show greater variability, especially at higher transfer counts, suggesting weaker synchronisation. Intermodal trips again occupy an intermediate position but with relatively high upper ranges, reflecting occasional inefficiencies in cross-modal coordination.

The additional distance-time analysis in panel C reinforces these patterns by introducing a clear speed differentiation between modes. GTT increases approximately linearly with Haversine distance for both bus and rail, but with distinct slopes: around 47 km/h for rail and 36 km/h for bus. This confirms that the observed GTT gap is not solely driven by network topology or transfer effects, but also reflects systematically different effective speeds. Rail maintains a consistently higher average speed over long distances, while bus services exhibit a lower speed regime and greater sensitivity to route geometry and intermediate stops.

Modal accessibility to European cities

The distributional and spatial patterns of accessibility, as defined in the Methodology section, reveal some stark modal differences. Figure 3 highlights that intermodal combinations generally outperform single modes, while transfers unlock substantial additional reach and central locations confer inherent advantages over peripheral ones.

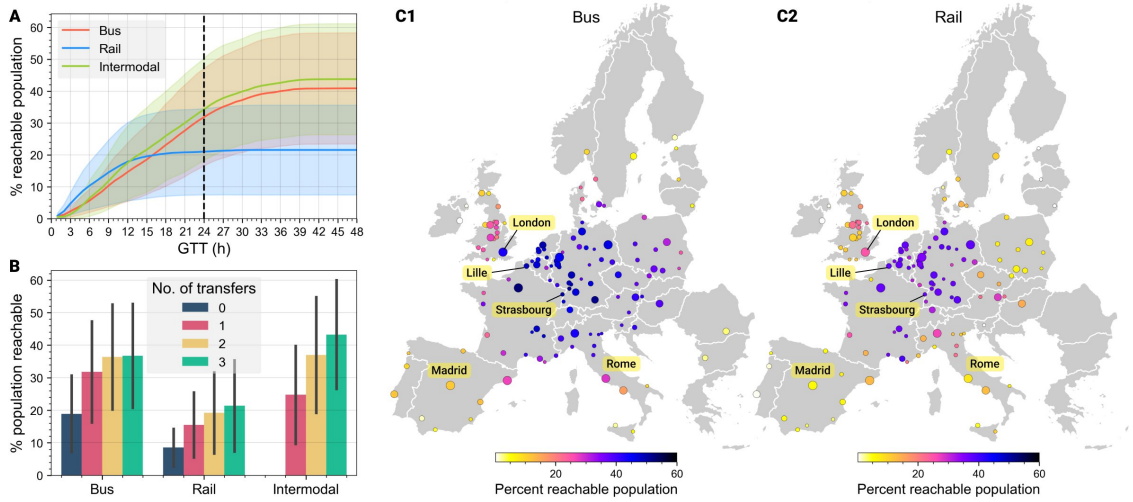


Figure 3: Modal reachability: (A) by GTT threshold, (B) by number of transfers, (C) map of reachability within 24 hours by (1) bus and (2) rail.

To unpack these dynamics, the figure first traces how accessibility accumulates as GTT thresholds relax, exposing fundamental differences in network scale and speed. Rail connectivity surges rapidly for short- and medium-haul trips, surpassing bus up to about 16 hours GTT, before plateauing around 15 hours, as its high-speed core captures most reachable FUAs early. Bus networks, by contrast, build coverage more gradually. Their spatially extensive coach routes that offset slower speeds with a broader span result in a much later saturation of the GTT at 38 hours. Intermodal routes combining bus and rail consistently achieve the highest reach across all thresholds after about 12 hours, though wide confidence intervals highlight city-specific variability in modal integration.

This temporal expansion hinges critically on transfers where the networks deliver the biggest leaps, as seen in panel B. A single within-mode transfer drives the sharpest gains – boosting bus reach from 19% (direct) to 32% and rail from 9% to 16% – with further within-mode steps yielding diminishing returns that reflect designs optimised for one-stop journeys, in line with previous observations (Curtale et al., 2023). Cross-modal transfers start weaker at one stop (24%, trailing bus-bus), but accelerate: by two transfers they match double bus-bus at 37%, then surpass triple bus-bus at 43%. Such patterns suggest intermodal links are vital for penetrating deeper, less-connected network layers, where coordinated interchanges turn longer paths into viable access.

Finally, the accessibility distribution shows a natural central tendency of geographical contouring. High bus accessibility traces an elliptical corridor from western France through Germany into Poland. For rail, the sphere of high accessibility is relatively small and concentrated in Germany, Benelux and France. Large but peripheral urban centres like Madrid, Rome and even London show less reachability than less popular yet centrally located travel destinations like Lille and Strasbourg, proving network centrality trumps city size in shaping effective reach of surface transport services.

4. CONCLUSION

This study offers a harmonised, service-level comparison of intercity bus and rail performance across the European Union and neighbouring countries, revealing a continent characterised by deep modal specialisation rather than genuine multimodal equivalence. Rail consistently outper-

forms bus in generalised travel time – with direct rail journeys averaging around three hours compared to nine for bus – and provides more direct, schedule-efficient connections concentrated in the dense western and central European core of France, Germany, the Benelux countries and the UK. Its accessibility, however, saturates rapidly at around 15 hours in terms of generalised travel time (GTT) as the high-speed rail network exhausts its reachable city pairs relatively quickly. Bus networks operate on a fundamentally different logic: slower and more variable, but spatially extensive and point-to-point in topology. Coach operators, most notably FlixBus, provide much of the connective tissue that links peripheral Europe to the mainland, including Finland via the Baltic states by bus-ferry combinations, northern Spain's cross-border corridors to France, and Southeastern European cities such as Bucharest, Sofia and Thessaloniki that remain weakly integrated into the core rail network. Bus accessibility accumulates more gradually but continues growing, only saturating near 38-40 hours, reflecting this broader geographic reach.

Transfers play a structurally decisive role for both modes but in an asymmetric way: a single transfer unlocks the largest gains in reachability and is associated with the steepest increase in GTT, while subsequent transfers yield diminishing returns. Intermodal combinations – mixing bus and rail – generally produce performance between the two single-mode benchmarks, though they are unique in generating higher two- and three-transfer accessibility than bus-to-bus travel alone, pointing to the particular value of coordinated interchanges in reaching deeper, less-connected parts of the network.

Several important caveats apply to these findings. The GTFS data used may be incomplete for some operators and regions, meaning that network coverage and service levels could be underestimated in parts of Eastern and Southeastern Europe. Modes are compared exclusively on the basis of generalised travel time; cost, comfort and safety are not considered, all of which are relevant to travellers' actual mode choice. Finally, the lack of same-city inter-station transfers and tighter restrictions on bus station identification may underestimate connectivity in certain cases.

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