Seamless borders? The transfer effect of cross-border travel in Europe

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Short summary

European long-distance rail is fragmented into national-oriented networks, creating impedance for international travellers. This study analyses cross-border impedance across Europe via transfer counts, using open General Transport Feed Specification (GTFS) data to construct a P-space graph of the European network. We introduce the maximal reach and country adjacency degree concepts to present the rail network structure in terms of concentric neighbouring relations between countries. We then characterised the countries in terms of connectivity to urban population, and number of transfers between country pairs. Our results reveal a clear core-periphery structure, where Western and Central European countries achieve high connectivity within 1–2 transfers, while peripheral countries require additional transfers. Directional heterogeneity is evident at borders, characterised by clusters of well-connected countries and poor core-periphery links. On average, transfer counts have a 1:1 relation with number of borders traversed, and high impedance locations generally agree with previous studies on cross-border travel speeds.
Keywords: long-distance rail; cross-border impedance; European rail; transfer minimisation; GTFS schedule; P-space graph representation

1 Introduction

Long-distance rail travel has seen a recent increase in political and academic interest, as part of the European Union's (EU) goal to achieve climate neutrality in the transport sector (Directorate-General for Regional and Urban Policy (European Commission) et al., 2020; DG REGIO, 2023; DG MOVE, 2021). High-speed rail (HSR) in particular is promoted as a climate-friendly alternative to aviation, and is a viable substitute for distances up to 500km in Europe (DG REGIO, 2023). However, despite heavy EU investments in rail infrastructure for the past decades, due to national decision-making processes the European rail system is fragmented along national lines (ECA, 2018; Witlox et al., 2022). Consequently, DG REGIO (2023) found that cross-border trips are on average slower than domestic trips, due to both slower on-track speeds and the need for transfers. The poor international connectivity of European rail ultimately limits the attractiveness of rail services to international travellers (Witlox et al., 2022). On average, less than 5% of international, intra-European trips are undertaken by rail, compared to 47% and 42% for air and private car respectively (Eurostat, 2026). The fragmented rail system creates friction points for travellers, especially the need to transfer in international trips, due to poor cross-border interoperability or lack of trans-European services (DG REGIO, 2023; Witlox et al., 2022).

Transfers are a significant impeding factor to travellers, being perceived as more burdensome than in-vehicle travel (DG REGIO, 2023; van Goeverden, 2009). However, the impedance from transfers in international trips is understudied in the long-distance rail segment, particularly the spatial distribution. In previous research, rail performance for international trips were studied in terms of air-rail competition (Avogadro et al., 2021; DG MOVE, 2021; Morgan et al., 2025). Such comparisons are done based on total travel time, including access/egress time, transfer waiting time and in-vehicle travel times. Transfers are thus expressed as total transfer time, but this ignores the impact of increasing transfer instances, which is also an impedance factor per se in mode choice (van Goeverden, 2009). For international rail, more transfers increases the risk of severe travel disruption, especially given the higher risk of delay and lack of uniformity of passenger rights across Europe (DG MOVE, 2021; Witlox et al., 2022).

Therefore, we hypothesise that the lack of cross-border integration leads to added transfers, and thus added impedance, whenever a passenger journey involves crossing a national border. Furthermore, we expect a spatially-heterogeneous distribution, where countries are better-connected to

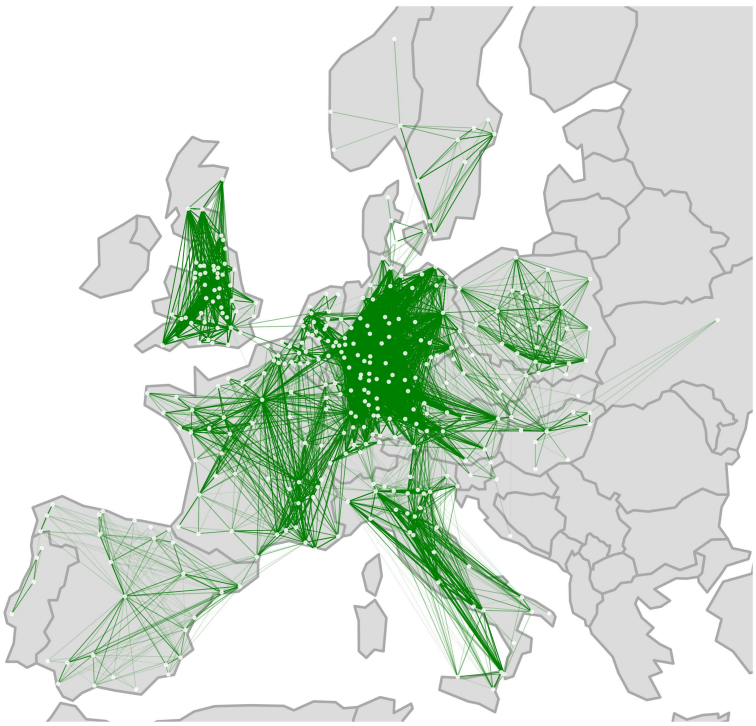


Figure 1: P-space network representation from European rail schedules data in GTFS.

certain neighbours than to others. In this study, we analyse the current level of rail connectivity, via the lens of reachable urban agglomerations within any given number of transfers. To assess the extent to which the nationally-oriented networks impact connectivity, we define and quantify the international travel impedance in terms of the number of transfers. We used open GTFS data to construct the European rail network, and describe the current structure of the network. Ultimately, this contributes towards assessing the impedance effect induced when crossing national borders, and thereby identifying accessibility bottlenecks within the European network for further analysis.

2 Methodology

We manually constructed a corpus of rail schedules from GTFS[1] feeds of various European countries. Countries which feature international rail connections are included, covering most of Europe (see Figure 1). Given the international HSR focus for this study, we include only intercity day train services. Therefore, rail routes spanning at least 2 cities are preserved, removing for example urban rail. Night trains are present in the data, but excluded by filtering out services that are in operation continuously between 12AM until 4AM.

The European rail network is represented as a P-space graph using the Python `igraph` package, where nodes are European Functional Urban Areas (FUA) (Lavalle et al., 2015), and edges represent the possibility to travel between 2 nodes via a single rail service, without an interchange. Here, an FUA represents a city and its commuting area. For parsimony, we excluded FUAs with a population under 200,000 inhabitants, amounting to 348 FUAs for this study. The resultant graph is shown in Figure 1.

We express the cross-border impedance in terms of number of transfers needed in the shortest paths of all FUAs. This is further processed into three metrics in the following subsections: maximal reach, connectivity to urban population, and mean number of transfers. Henceforth, the mathematical notation for origin and destination are set as ij for FUAs and IJ for countries.

[1]GTFS: General Transit Feed Specification

Maximal reach

The maximal reach metric, ρ_i, denotes the furthest distance that an FUA can access from rail services, in terms of country adjacency degree. The adjacency degree can be viewed as the minimum number of national borders to cross to traverse countries I and J. This formulation views each country's connectivity as the ability to reach countries in its concentric neighbourhood. An immediate neighbour would be degree 1, 2 for 2nd-degree neighbours, and et cetera. This corrects the geographic centrality of countries, which conventionally favours Central European countries. We first define the adjacency degree D in terms of the *country-adjacency* graph G_C, which represents the physical adjacency relations between the set of European countries C. An edge between countries I and J exist if any of 2 conditions are met: both countries share a contiguous land border, or connected over water via rail tunnels, bridges, or ferries. The adjacency degree formulation between countries is:

$$D(I,J) = D(J,I) = \begin{cases} 0 & \text{if } I = J \\ \min_{p \in \mathcal{P}_{IJ}}\{|p|\} & \text{if } \mathcal{P}_{IJ} \neq \emptyset \\ \text{null} & \text{otherwise} \end{cases}$$

where $\mathcal{P}_{IJ}$ is the set of topological paths p between countries. Therefore, we define an FUA's maximal reach, ρ_i, as:

$$\rho_i = \max_{j \in N_i^1}\{D\left(C_f(i), C_f(j)\right)\}$$

where N_i^1 is the set of neighbouring nodes of order 1 from FUA i excluding itself, and C_f is the FUA-to-country mapping function.

Reachable urban population per transfer

Reachable urban population, Φ, is the fraction of total urban population (sum of all FUA populations), that are reachable within n transfers. This reflects transport accessibility norms, indicating access to populous urban areas, which are more geographically-important. However, it is sensitive to the geographic centrality and population distribution of FUAs, and favours Western European countries. For an FUA, the metric is defined as follows:

$$\Phi_i^t = \frac{\sum_{j \in N_i^{t+1}, j \neq i} P_j}{\sum_{j \in \mathbb{V}, j \neq i} P_j}$$

where P_j refers to the population size of FUA j, $\mathbb{V}$ the set of all FUA nodes. N_i^{t+1} refers to the neighbourhood of FUA i of order $t+1$ in the P-space graph; it refers to the number of accessible neighbours within t transfers. The weighted sum for a country I, over all of its component FUAs:

$$\overline{\Phi}_I^t = \frac{\sum_{i \in \mathbb{V}_I} \Phi_i^t \cdot P_i}{\sum_{i \in \mathbb{V}_I} P_i}$$

where $\mathbb{V}_I$ is the set of FUAs within country I:

$$\mathbb{V}_I = \{i \in \mathbb{V} | C_f(i) = I\}$$

Cross-border impedance

Lastly, the cross-border impedance metric is the average number of transfers needed to traverse between FUAs of 2 countries. This is weighted by the sum of populations between origin and destination FUAs. In the results, two aggregates are shown: per destination country, and for all destination countries of the same adjacency degree. The weighted mean function is:

$$\overline{T}(\mathbb{I}, \mathbb{J}) = \frac{\sum_{i \in \mathbb{I}} \sum_{j \in \mathbb{J}} [T_{ij} \cdot (P_i \cdot P_j)]}{\sum_{i \in \mathbb{I}} \sum_{j \in \mathbb{J}} (P_i \cdot P_j)}, \text{ where } \mathbb{I} \cap \mathbb{J} = \emptyset$$

where $\mathbb{I}$ and $\mathbb{J}$ refer to the set of origin and destination FUAs respectively, T_{ij} is the minimal number of transfers between FUAs i and j, and P is the FUA population. Note that the decision to multiply origin and destination population sizes would favour more-populous FUA pairs. We calculate the metric per country pair and per adjacency degree:

$$\overline{T}_{I,J} = \overline{T}(\mathbb{V}_I, \mathbb{V}_J)$$

$$\overline{T}_{I,D=d} = \overline{T}(\mathbb{V}_I, \mathbb{V}_{D=d})$$

where $\mathbb{V}_{D=d}$ indicates the set of FUAs of adjacency degree d:

$$\mathbb{V}_{D=d} = \{i \in \mathbb{V} | D(C_f(i)) = d\}$$

3 Results

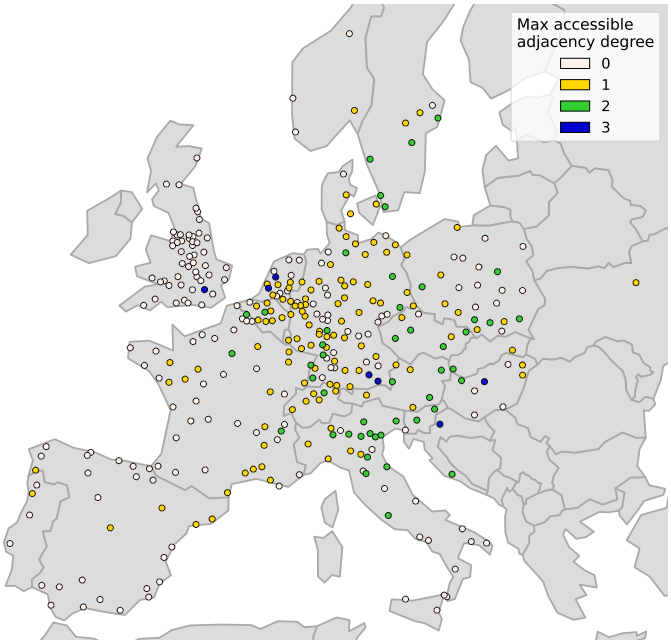
The results are presented at several perspectives. First the maximal reach is shown for all FUAs (Figure 2a), depicting the spatial hierarchy of FUAs and their role in providing international connectivity. Next, we show the reachable European urban populations considered (Figures 2b and 3), indicating the fraction of urban population reachable per added transfer threshold. Lastly, we show the outputs for the number of transfers (Figures 4 and 5), showing the number of transfers needed to reach destinations of increasing country adjacency degree, and to travel across country borders.

Maximal reach

Figure 2a shows the countries' international hubs, and the maximal distance accessible in terms of country adjacency degree. As a whole, half of FUAs in Western and Central Europe have substantial international connections. 173 out of the total 348 FUAs offer at least 1 direct international service, of which 119 connect directly to a neighbouring country (degree 1). However, only 54 FUAs across Europe have a degree of 2 or more. 175 FUAs only serve domestic routes, requiring connections to hub FUAs for international trips. Notably, certain hubs in Poland, Austria, and Italy have hubs providing long-distance services, up to 2 adjacency degrees away. Additionally, looking at national distributions of degrees, countries such as France, Spain and Britain strongly rely on hub FUAs, while Germany, Italy and Belgium have more FUAs offering international connections. The low amount of FUAs possessing a degree 2 or 3 suggests that multiple transfers through such hub FUAs are needed to access any other European country.

Reachable urban population

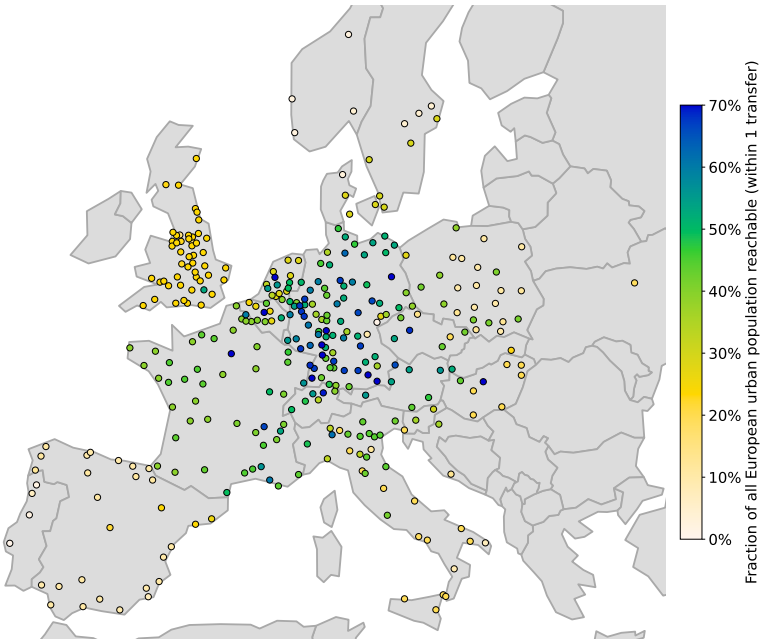
Figure 2b provides a geographical overview of FUAs' reachable urban population within 1 transfer, while Figure 3a provides an aggregate view of countries' connectivity per added transfer threshold. Figure 2b highlights a clear core-periphery structure, centred around central and western countries. Within this core, it is possible to reach 50% or more of urban population within 1 transfer, with some hub FUAs reaching up to 70%. However, this connectivity decreases sharply outside this core, indicating the need for extra transfers. Notably, Spain and Poland have poor connectivity despite neighbouring the core, suggesting poor service linkage to core countries. Combining the maximal reach results in fig. 2a and fig. 2b, a general pattern can be seen. A country with high geographic centrality combined with a high proportion of FUAs with high reach, leads to high connectivity to the urban population. In countries such as France and Germany, hub FUAs are capable of reaching up to 70% connectivity, while domestic-only FUAs can reach up to 40–50%. However, peripheral countries such as Sweden, Poland, and Spain would require higher reach or more transfers. Hub FUAs in Poland and Italy have up to a maximal reach of 2, but only can access at most 50% of the urban population within one transfer, equivalent to the smaller, domestic-only FUAs in the core. Figure 3a shows the countries' connictivity to all urban populations per transfer $\overline{\Phi}_I^t$, and the added gain per transfer. The horizontal axis (countries) is sorted by best performance at the 1-transfer threshold. The output is split into 3 bands: Germany-Netherlands (DE-NL), Slovakia-Spain (SK-ES), and Norway-Portugal (NO-PT). The first "core" band comprises most of the Western and Central countries, achieving at least 50% population connectivity within a single transfer, and almost 80–90% in 2 transfers. However, countries surrounding this core in the second band need one additional transfer to match the connectivity of the core. Within these two bands, it is generally possible to access all populations from any country at 3–4 transfers. Lastly, the last band of Norway and Portugal have the worst connectivity. From the marginal gain subfigure, most of the connectivity is generated by 1–2 transfers for the core, and 1–3 transfers for the 2nd



Distribution of degrees [Number of FUAs]

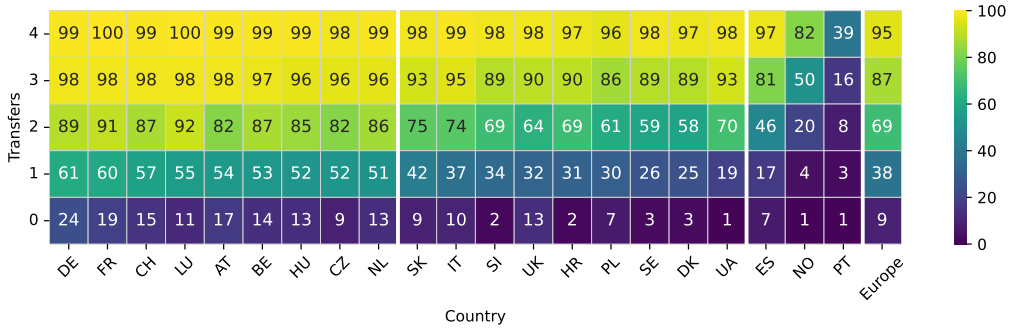
Degree 0 (domestic)	Degree 1	Degree 2	Degree 3
175	119	47	7

(a) Map of FUAs' maximal reach in terms of country adjacency degree, indicating the furthest possible rail service available. This also shows the hierarchy of FUAs in providing international connections for their respective countries. A reach of degree=0 indicates domestic access, degree=1 indicates connectivity to immediate-neighbouring countries, and et cetera.



(b) Map plot of rail connectivity to all European urban population within 1 transfer, as a fraction of total urban population.

(a) Percentage of all European urban populations reachable within N transfers.



(b) Percentage growth of European urban populations reachable per transfer.

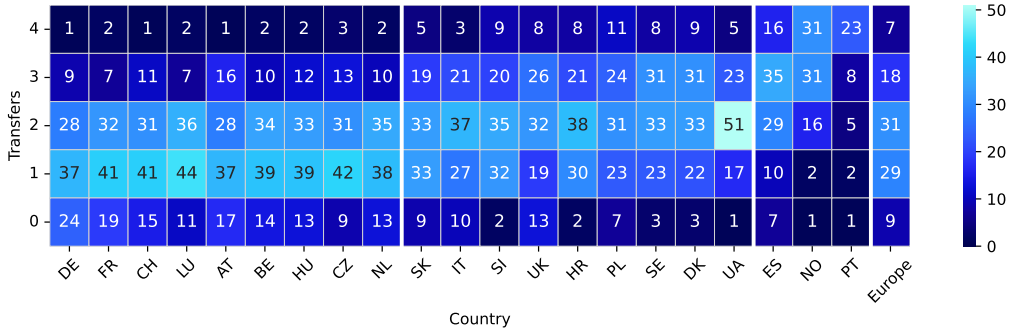


Figure 3: Heatmaps indicating the percentage of reachable total urban population, weighted by the product of the population of origin and destination FUAs. 3 bands can be seen here: a core and two periphery bands. The cumulative heatmap (a) suggests that at least 4 transfers are needed to reach all FUAs. The percentage growth heatmap (b) indicates a high reliance on 1–3 transfers needed for geographic coverage.

band. This suggests a high reliance on transfers for international access, which is shown as well in Figure 4a.

International vs. domestic transfers

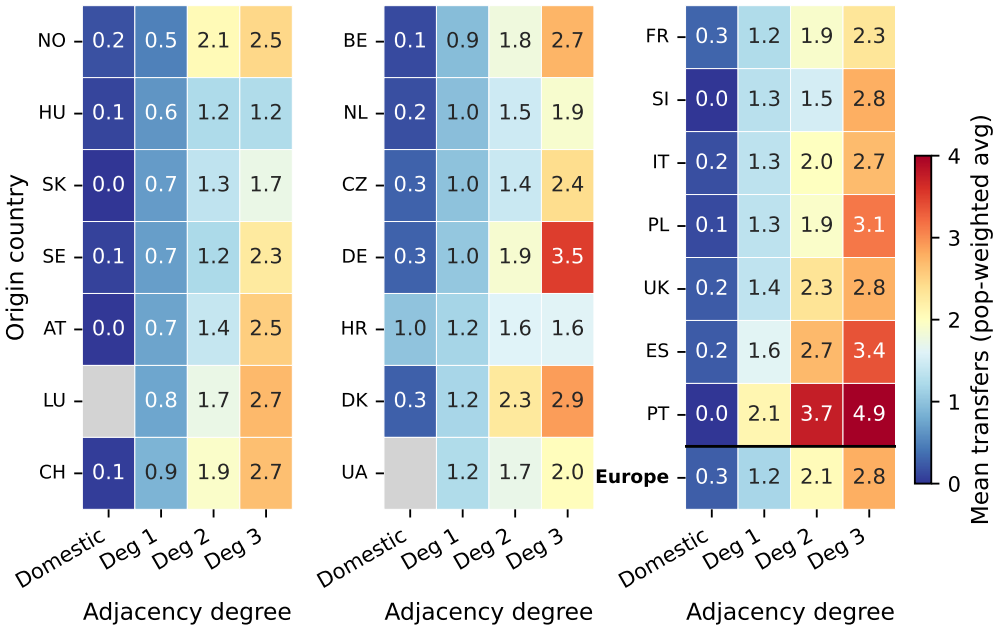
Figure 4 shows the number of transfers from a country to other countries, averaged per country adjacency degree ($\overline{T}_{I,D=d}$). The values are more optimistic due to the product-based weights, which favours populous ODs. The subfigures 4a and 4b shows the total transfers and difference between adjacency levels respectively. In both plots, a European-wide average is taken over all FUA pairs.

In Figure 4a, countries are sorted by their degree-1 values, indicating mean effort to reach immediate neighbours. The degree-1 values are notable, as they can be directly influenced by the origin country's rail services. Most countries are usually able to provide domestic access within 1 transfer, and access to their immediate neighbours (degree-1) within 1–2 transfers. The countries in the leftmost column are capable of reaching a neighbouring country within 1 transfer, but tend to be countries with fewer FUAs. Most countries are able to access degree 2 neighbours within 2 transfers, and degree 3 within 3 transfers. From Figure 4b, the number of transfers increase monotonically per degree. On average, the European network requires about 1 transfer per degree. Notably, Norway has a direct connection with its immediate neighbour, but a significantly poorer value for degree 2 (Denmark). Countries on the rightmost column usually need 1 or more transfer to access their neighbours. Here, Italy and Spain are notable, as they have capable domestic HSR networks, but poor international connectivity.

Figure 5 shows the mean number of transfers between 2 bordering countries ($\overline{T}_{I,J}$). Notably, directional heterogeneity is visible amongst countries. For example, fewer transfers are needed to travel from France to its northeastern neighbours, compared to its southern neighbours of Spain and Italy. The heterogeneity indicates difference in direct services between countries, and potentially the need for cross-border infrastructural improvements.

Additionally, clusters of well-connected countries can be seen, e.g. {Czech Republic, Austria, Hun-

(a) Mean number of transfers between countries, by country adjacency degree



(b) Difference in number of transfers between countries, by country adjacency degree

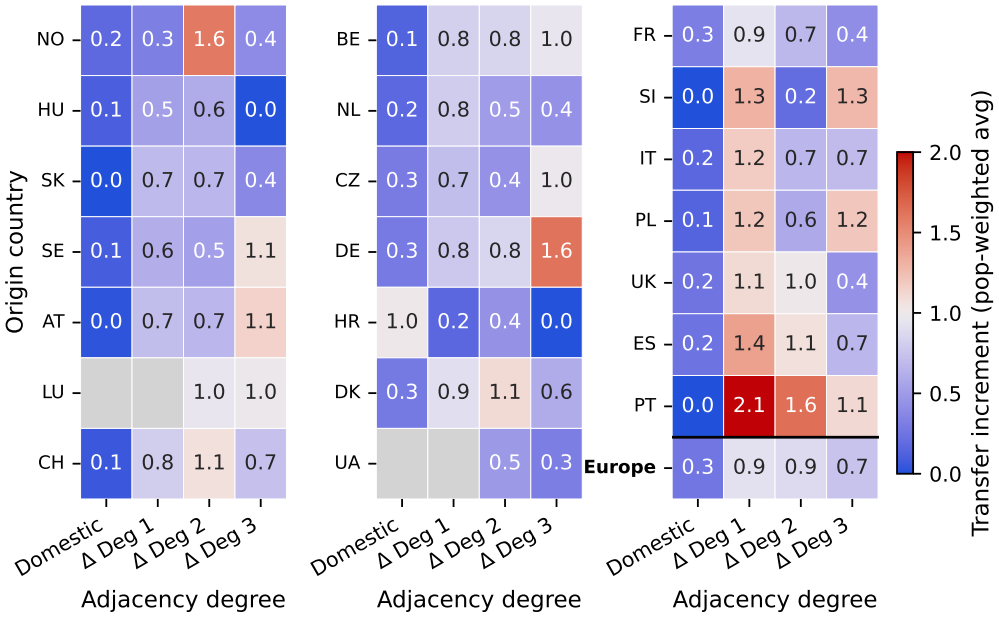


Figure 4: Mean number of transfers needed to travel between FUAs, grouped per adjacency degree and weighted by the product of origin and destination population weights. The results are sorted by degree-1 values, indicating the mean effort to reach immediate neighbours. Blank degree-0 values shown in UA, LU indicate that there is only 1 FUA for the country.

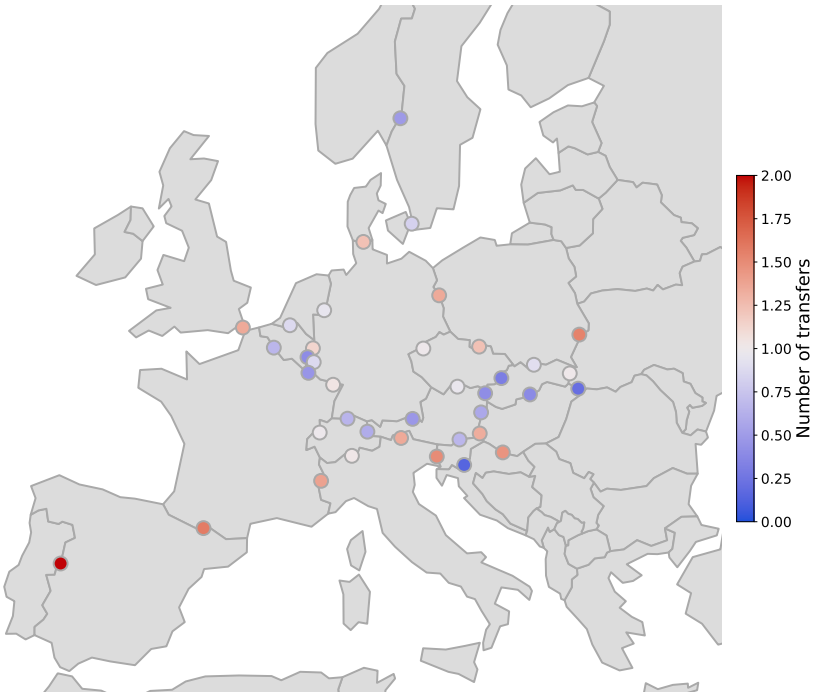


Figure 5: Average number of transfers needed to traverse the borders between countries, weighted by the product of the populations of origin and destination FUAs.

gary, Slovakia}, {Sweden, Norway, Denmark}, {Germany, Switzerland, Austria}, and {France, Luxembourg, Belgium}. Country size may play a factor: larger countries such as France and Germany may require internal transfers for most of their FUAs. When compared with the results from DG REGIO (2023, p. 7), some commonalities and differences are present. The results broadly agree at poor-performing borders, e.g. Spain-Portugal, Italy-France, and Germany-Poland. These results are logical, as poor transfer performance affects travel speed. However, their results disagree at the {Czech Republic, Austria, Hungary, Slovakia} cluster, where poor straightline speeds are present. This may be that more direct connections can still be undermined by slow on-track speeds, or the presence of newer rail services added between 2019 and 2025.

Discussion

We examined the relationship between number of country border traversals to number of transfers for international European rail trips. The findings broadly agree with previous literature on the fragmentation of the European rail network, and on country borders with poor rail performance. Almost all countries provide good domestic connectivity within 1 transfer to urban areas. However, for international trips, more transfers are needed per added border, especially countries that rely on central hubs such as France and Spain. The high reliance on transfers suggests also a need to improve the transfer quality of travellers, for example via scheduling alignment and in-station amenities. We see that only some core countries with high connectivity offer services that span 3 or more countries. This suggests an insufficiency in long-distance services in periphery-core links such as the French-Spanish and German-Polish borders. Conversely, we see highly-connected country clusters, where the countries have more direct connections to each other than non-group neighbours. The performance of these clusters may motivate study and consequently policy insights on inter-country collaboration.

Methodologically, the analysis on transfer counts partially elucidates the cross-border connectivity problem, such as with Italy and Spain. The disagreement with DG REGIO (2023) on Central European countries however, highlights the methodological limitation of excluding travel speed. This motivates future extension on jointly including both aspects. The study also introduces two presentation devices: the maximal reach metric and country adjacency degree. The maximal reach metric presents the network structure of European rail, linking between the service provision to the population connectivity and transfer counts metrics. The adjacency degree formulation attempts

to compare countries in terms of impedance to concentric neighbours, and provides an aggregate indication of increasing transfers per added border from an origin country. At lower degrees, it is useful for highlighting the increase in impedance between domestic and international trips. However, its descriptive power becomes limited under spatial heterogeneity, as it cannot account for country size and travel distance, and the same country may have varying impedance values with its neighbours. Additionally, at higher degree values, the transfer counts would be primarily influenced by the rail network quality of the countries traversed. Therefore, for future extension, we aim to develop a characterisation of the impedance contribution from network elements. This would be valuable in targeted improvements of rail service or infrastructure at these locations. Lastly, the application of open GTFS data for the European international rail network offers novel opportunities for rail accessibility studies. However, the data coverage can be improved for future research, as data in Eastern European countries (Balkans and Baltics) are not available. Another challenge exists in terms of translating new infrastructural developments, such as the TEN-T projects, into new potential services for analysis.

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