Assessing the spatial overlap between urban fragmentation and residential segregation in European cities.

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1 Introduction

Residential segregation, defined as the uneven distribution of social groups in space, represents a persistent challenge in urban environments (Reardon and O'Sullivan, 2004; Tammaru et al., 2015). This spatial separation has been consistently linked to disparate outcomes in education, employment, and health for disadvantaged populations (van der Greft and Fortuijn, 2017; Owens, 2018; Nieuwenhuis et al., 2020; Tóth et al., 2021). Research has long documented how residential segregation patterns emerge alongside urban development. In particular, scholars argue that urban fragmentation — the partition of urban space through physical barriers such as railways, motorways, and waterways — may encourage residential segregation by creating tangible boundaries within cities enabling social groups to isolate themselves from others Graham and Marvin (2001). The interaction between these phenomena has given rise to what scholars term the "wrong side of the tracks" effect, where physical infrastructure serves as both a literal and symbolic barrier between social groups (Noonan, 2005).

This relationship between urban fragmentation and residential segregation has been extensively documented in the United States, where it emerged within the context of explicit segregation policies. However, the European context presents a markedly different case. Residential segregation in Europe emerged organically from household residential choices and mobility patterns, and its potential association with urban frontiers fundamentally differs from the US context where infrastructure was deliberately used to engineer segregation.

This contrast raises fundamental questions about the universality of the "wrong side of the tracks" phenomenon. While the mechanism linking infrastructure to segregation is well-understood in the American context, its applicability to European cities remains uncertain. Investigating this relationship in the European context would reveal whether physical infrastructure do associate with residential segregation independently of explicit separation policies. This question has important policy implications: if no systematic association exists, efforts to reduce physical barriers may not be necessary from a segregation perspective.

Despite the theoretical importance of this question, there has been a notable absence of large-scale quantitative studies examining this relationship across European cities. Our research makes two primary contributions to address this gap. First, we provide a comprehensive empirical analysis of the relationship between urban infrastructure and social segregation patterns across 490 cities in eight European countries. This large-scale study allows us to assess whether the "wrong side of the tracks" phenomenon emerges organically in contexts without historical segregation policies. Second, we develop a novel methodological framework for quantifying the association between two distinct spatial patterns, which can be applied beyond segregation studies to other urban research contexts.

2 Case study and data

Our analysis covers 496 urbanized areas of more than 50,000 inhabitants across eight European countries: the United Kingdom, France, Germany, Spain, Italy, Portugal, Ireland, and the

Netherlands. We focus on residential segregation of migrants, using harmonized demographic data consolidated for year 2011 in these 8 countries, providing the spatial distribution of the population with a migration background at a 100x100 m^2 spatial resolution (Alessandrini et al., 2017). Data on roads, railways, and waterways are extracted from the OpenStreetMap (2025) database.

3 Methodology

Our methodology aims to quantify the spatial overlap between urban fragments and demographic regions across European cities. The approach consists of three main stages. First, we partition urban space into demographically homogeneous regions using spatial clustering of census data (subsection 3.1). Second, we create a distinct partition of the same space using physical barriers such as railways, major roads, and waterways to define urban fragments (subsection 3.2). Third, we develop a novel approach to measure the overlap between these two spatial partitions, comparing the observed correspondence between urban fragments and demographic boundaries against what would be expected from randomly generated synthetic partitions (subsection 3.3). We systematically apply this methodology to all cities in our dataset, allowing us to assess whether infrastructure-defined fragments consistently align with patterns of residential segregation.

3.1 Regionalization of the demographic data

We employ a regionalization approach to partition space based on demographic data. This process delineates demographically homogeneous regions from census data using spatially-constrained agglomerative clustering, inspired from the work of Spierenburg et al. (2024). We illustrate it in figure 1 for the city of Freiburg im Breisgau. Adjacent cells with similar demographics and iteratively merged together to form spatial clusters, called demographic regions in this study. Figure 1 indicates the demographic regions overrepresenting migrants identified by the regionalization approach in map C. A spatial moving average is applied before the clustering process to filter out small-scale fluctuations (map B in figure 1). More details about the method are available in the work of Spierenburg et al. (2024).

3.2 Partitioning study area into urban fragments

We partition urban space into fragments using physical infrastructure that creates tangible boundaries within cities. These urban fragments are defined as contiguous groups of cells bounded by three types of infrastructure: railways, major transportation arteries (motorways and primary roads), and waterways (rivers and canals). Figure 2 illustrates this process for Freiburg im Breisgau, showing the study area and the network of physical barriers (A) and the resulting urban fragments (B).

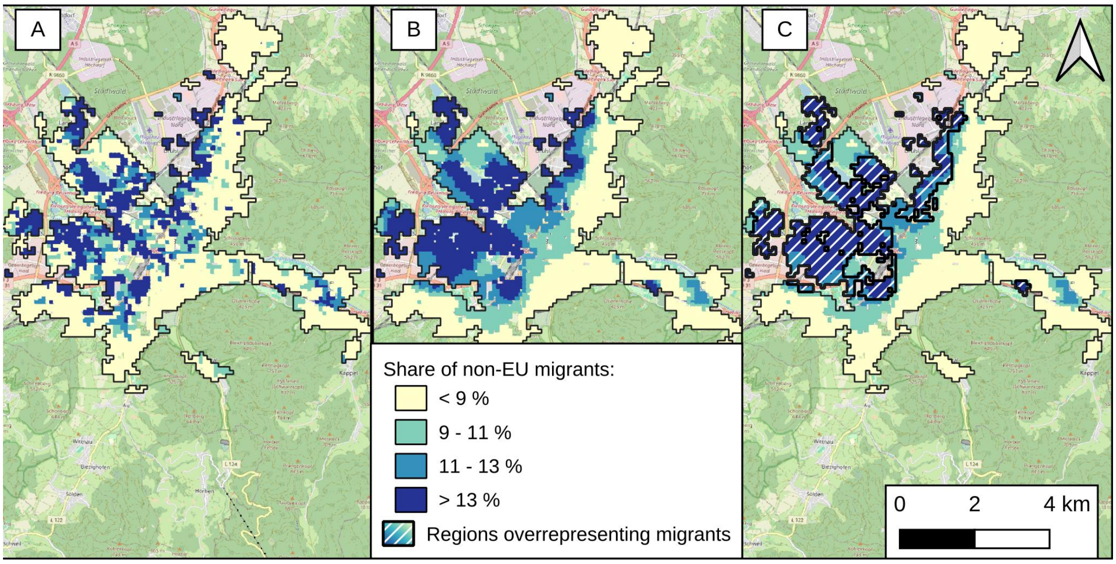

Figure 1: Illustration of the regionalization process for the case of Freiburg im Breisgau, where the non-EU migrants represent 11% of the total population in the study area. A: Share of non-EU migrants living in a spatial units. B: Spatially-averaged share of non-EU migrants. C: Regions overrepresenting non-EU migrants, other regions are excluded for better visibility.

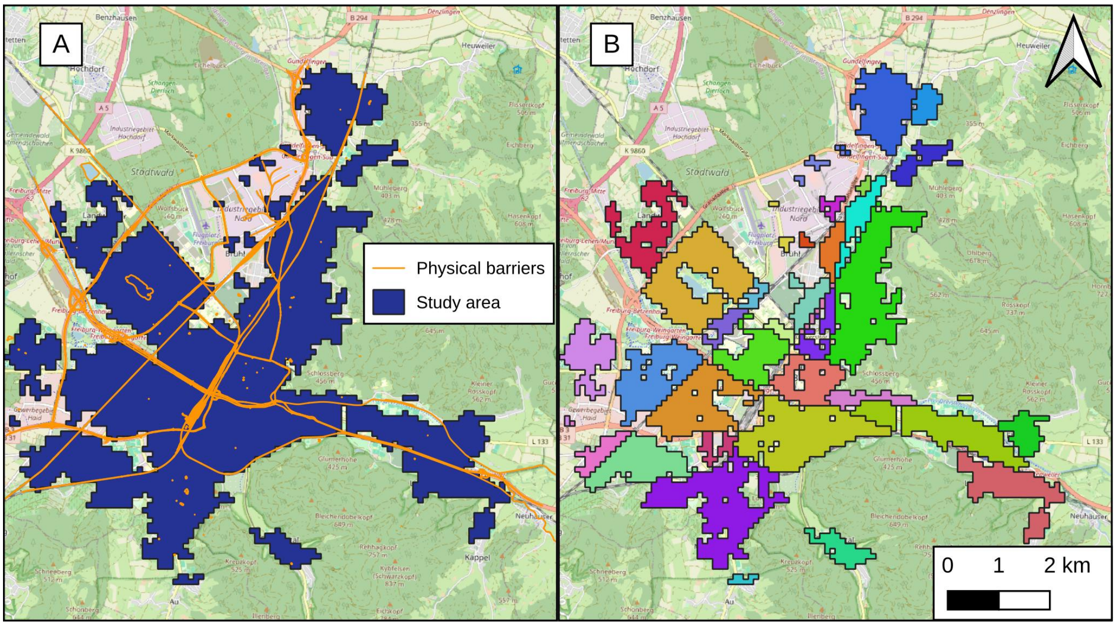

Figure 2: A: Physical barriers (railways, main roads, waterways) in the study area. B: Fragmentation of space resulting from physical barriers.

3.3 Measuring the overlap between urban fragmentation and residential segregation

We measure the correspondence between urban fragments and demographic regions using a purity score metric π (equation 1). For each fragment m, we identify the demographic region d that contains the largest share of the fragment's population. The overall purity score sums these maximum population overlaps across all fragments M, normalized by the total population N.

$$\pi_m = \frac{1}{N} \sum_{m \in M} \max_{d \in D}(population(m \cap d)) \tag{1}$$

The purity score can be seen as a measure indicating how well we can reconstruct demographic regions using urban fragments as building blocks. Figure 3 illustrates this by showing the original demographic regions (A), their reconstruction using urban fragments (B), and the spatial agreement between these partitions (C).

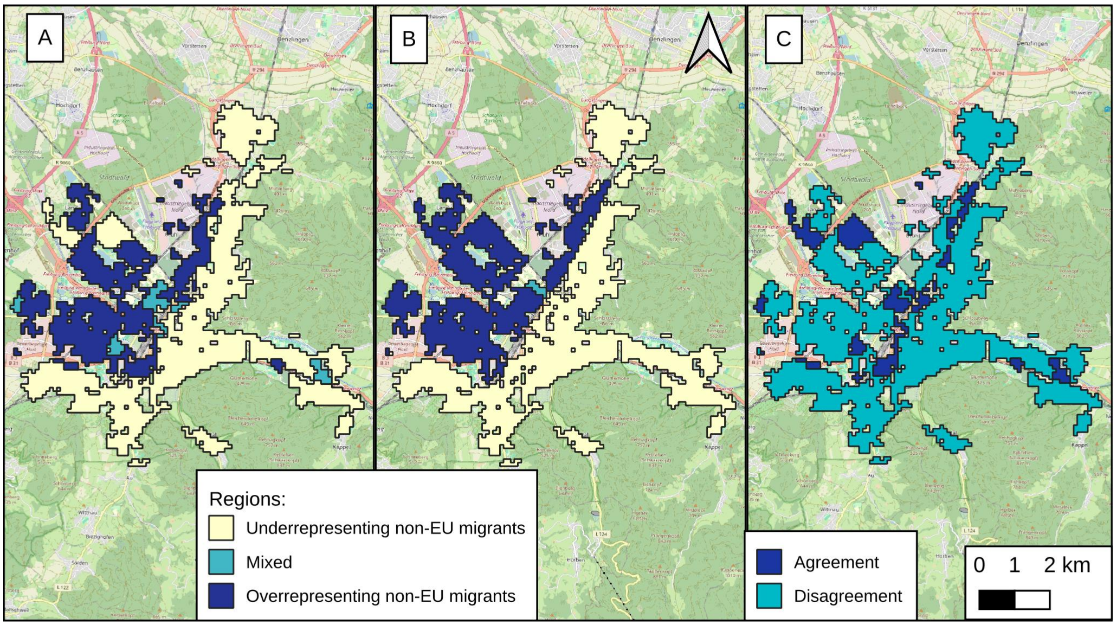

Figure 3: A: Demographic regions identified from the regionalization approach. B: Demographic regions reconstructed using urban fragments. C: Agreement between the two partitions.

To determine whether the observed spatial correspondence is meaningful, we develop a Monte Carlo testing procedure. This approach addresses a key methodological challenge: high purity scores could occur by chance, particularly with fine-grained urban fragmentation. For instance, a partition where each cell is its own fragment would perfectly match any demographic pattern despite lacking structural significance.

Our testing procedure generates 500 synthetic spatial partitions, each preserving the number of fragments from the observed urban pattern but with randomly assigned boundaries. This creates a null distribution of purity scores that could arise by chance. The position of the observed purity score within this distribution (expressed as a quantile) determines whether the spatial correspondence between urban fragmentation and residential segregation significantly exceeds random expectation. Figure 4 summarizes this approach.

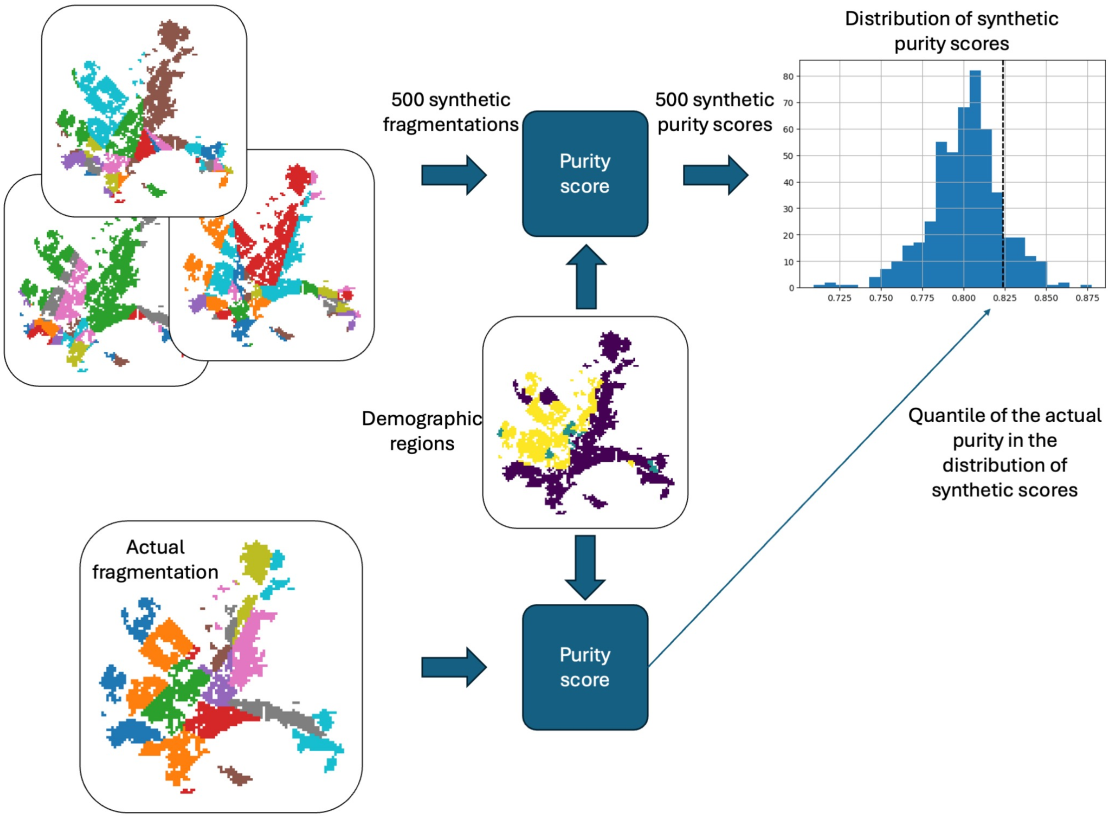

Figure 4: Measuring the significance of the purity score by comparing to a synthetic distribution.

4 Illustrative results

Our preliminary analysis of eight cities, one from each country in our dataset, reveals substantial heterogeneity in the relationship between urban fragmentation and residential segregation. The purity scores show no consistent pattern across these pilot cases, with some cities exhibiting strong spatial correspondence between physical barriers and demographic boundaries, while others show weak or inverse relationships.

Three cities demonstrate significant alignment between infrastructure and demographic boundaries. In Freiburg (q = 0.996), migrants are overrepresented in the North-West quadrant, an area clearly delineated by the railway connecting Hauptbahnhof to the Rheintalbahn and the Bundesstraße (A and B in figure 5). Similar strong spatial correspondence appears in the Hague (q = 0.996) and Rome (q = 0.96).

In contrast, Barcelona and Lyon (both q = 0.002) show an inverse pattern, where demographic regions align less with urban fragments than would be expected by chance. In these cities, areas with high migrant populations often center around transportation nodes and extend across infrastructure boundaries, as in the Nou Barris district from Barcelona (C in the bottom map of figure 5). Limerick (q = 0.44) represents an intermediate case, where the relationship between infrastructure and demographic boundaries appears random.

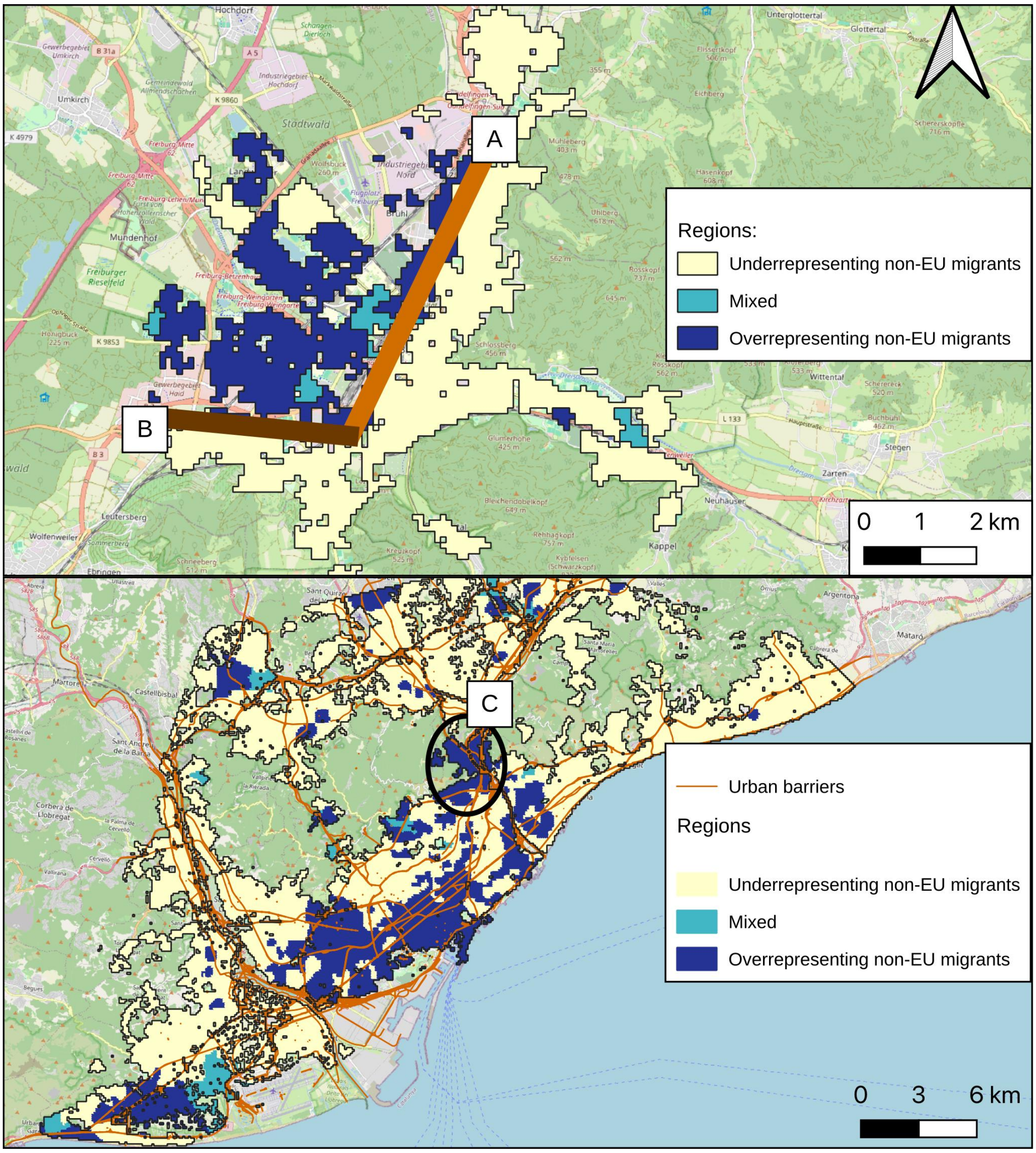

Figure 5: Qualitative assessment of the overlap between urban fragments and demographic regions for the city of Freiburg im Breisgau. A: Railway connecting Freiburg Hauptbahnhof to the Rheintalbahn. B: Bundesstraße, a major road in the South-West of Freiburg. C: Demographic regions centered around physical barriers.

This variation in spatial patterns challenges the universality of the "wrong side of the tracks" phenomenon in European cities. Our next analytical phase will extend this investigation to all 496 cities in our dataset, examining whether these infrastructure-segregation relationships correlate with city-specific features such as size, geographic location, or historical development patterns.

5 Conclusion and outlook

Our study makes several important contributions to understanding the relationship between urban infrastructure and social segregation in European cities. First, we demonstrate that there is no universal association between urban fragmentation and residential segregation, challenging the assumption that physical barriers inevitably reinforce social boundaries. This finding suggests that efforts to reduce physical barriers may not uniformly impact segregation patterns across European cities. Second, our methodological framework provides a robust approach for analyzing spatial pattern associations, combining regionalization analysis with Monte Carlo simulations to quantify spatial relationships while controlling for chance alignments.

These findings have important implications for urban policy and planning. The heterogeneous relationship between infrastructure and segregation across cities suggests that local context matters more than previously thought. While some cities show strong alignment between physical barriers and demographic boundaries, others exhibit patterns that contradict the "wrong side of the tracks" hypothesis. This variation indicates that universal policies targeting physical barriers may not be effective for addressing residential segregation. Instead, cities may need tailored approaches based on their specific spatial and social patterns.

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