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Aligning transit provision with urban morphology: A diagnostic assessment of Porto and Cagliari

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ABSTRACT

Transit accessibility in cities is shaped not only by service provision but also by the extent to which transit networks align with the structural hierarchy of streets. This paper develops a reproducible, data-efficient framework that integrates angular segment analysis from Space Syntax, proximity-based transit catchments, and population-weighted exposure measures to assess how well transit stops correspond to high-integration corridors. Two indicators operationalise this assessment: the Gap Index, which identifies the share of population exposed to high-integration corridors lacking nearby transit service, and the Equity Ratio, which compares exposure levels across demographic groups. The framework is applied to Porto and Cagliari, two Mediterranean port cities that share comparable urban morphologies but exhibit contrasting mobility outcomes. Findings reveal a strong divergence. Porto demonstrates complete proximity coverage of its structurally high-integration corridors, indicating a close alignment between transit routing and the spatial configuration of the street network. However, Cagliari displays a pronounced proximity deficit, with a substantial share of high-integration corridors lying outside 300 m transit stop catchments. These results suggest that differences in accessibility between the two cities arise not from population distribution or morphological potential but from strategic choices in transit routing. The study shows how morphology-aware indicators can help planners detect accessibility gaps that conventional supply-side assessments overlook and highlights the value of integrating spatial configuration analysis into routine diagnostic practices. The proposed framework offers a transferable basis for monitoring alignment between street structure and transit provision, supporting more responsive and equitable mobility strategies in port-city contexts.

1. Introduction

Port cities have historically functioned as gateways for trade and cultural exchange, fundamentally shaping their regional economies and spatial structures (Ducruet, 2020). In the 21st century, however, containerisation and automation are transforming port operations, prompting cities to reimagine their waterfronts. Former industrial zones are being converted into spaces for tourism, leisure, and housing. While these projects promise urban revitalisation, they raise critical questions about spatial and social equity (Rao, 2024). A central challenge is maintaining accessibility—defined not merely as physical proximity but as the ability for all residents to reach jobs, services, and opportunities (Lanza et al., 2023). Too often, redeveloped waterfronts feature high-quality public spaces alongside fragmented mobility networks, creating uneven access. The key question is not just how to design attractive waterfronts, but how to ensure they are seamlessly connected to the broader city for all users (Toomey et al., 2021). These challenges are not confined to individual cities but reflect a broader global concern in urban planning, where mismatches between urban form and transport provision contribute to uneven accessibility outcomes across diverse geographic contexts. From rapidly urbanising regions to historically layered European cities, the alignment between spatial configuration and mobility systems has emerged as a critical issue in debates on sustainable urban development, transport equity, and inclusive accessibility. Despite this, existing analytical approaches often evaluate transit provision independently of the underlying spatial structure of the street network, limiting their ability to detect systemic misalignments.

Despite the growing attention to equitable mobility and port–city renewal, transit accessibility studies rarely integrate the structural logic of the street network into their analyses. This omission is consequential:

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cities undergoing waterfront redevelopment often experience shifts in movement patterns that require diagnostic tools capable of linking urban form, transit routing, and population vulnerability. This paper addresses this gap by proposing an integrated morphology–transit diagnostic framework that couples configurational centrality with transit stop coverage and demographic exposure. Two indicators, the Gap Index (GI) and Equity Ratio (ER), are developed to quantify alignment or misalignment between inherent movement potentials and delivered transit access. The framework is applied to two contrasting medium-sized port cities, Porto (Portugal) and Cagliari (Italy), to examine how planning decisions shape accessibility outcomes.

This challenge is particularly acute in Southern Europe, where dense, historically layered urban fabrics complicate redevelopment (Abrahamse & Deneweth, 2022). The Mediterranean context, with its narrow streets, mixed land uses, and reliance on walking and public transport, means the relationship between street network integration and transit provision is paramount for urban accessibility (Battarra & Mazzeo, 2022). A growing body of research shows that redevelopment can disrupt established movement patterns, sometimes displacing activity from integrated corridors or overlooking neighbourhoods with high mobility needs (Wan et al., 2023). The interplay between street network structure and public transport coverage is therefore crucial.

This is especially true for children and elderly residents, who are more dependent on walking and public transport and are thus highly vulnerable to accessibility gaps. Existing studies rarely operationalise morphology–transit alignment as a measurable indicator; this study fills that gap (Kapsalis et al., 2022; Tassadiq et al., 2025). When transit provision fails to align with structurally integrated streets, their participation in urban life can be severely curtailed. This creates a need for diagnostic tools that integrate morphological, functional, and demographic dimensions. Space syntax offers a powerful approach by quantifying the integration of street networks, a measure of how easily each segment can be reached from all others. When combined with data on transit stops and population characteristics, it can reveal where structural connectivity is either reinforced or undermined by transit provision (Liu et al., 2023). To address this gap, the study is guided by the following research question: to what extent does public transport provision align with the configurational structure of the street network, and how does this alignment influence population exposure to accessibility deficits in port-city contexts?

More specifically, the analysis examines whether transit stops are systematically located along high-integration corridors representing the structural backbone of urban movement and whether deviations from this alignment generate measurable disparities in accessibility across demographic groups. Building on this, the study acknowledges two analytical propositions: (1) that effective transit systems reinforce the configurational hierarchy of the street network, and (2) that misalignment between transit provision and high-integration corridors leads to disproportionate exposure to underserved conditions, irrespective of underlying demographic distribution. These propositions are operationalised through the Gap Index (GI) and Equity Ratio (ER), enabling a comparative assessment of morphology–transit alignment in Porto and Cagliari. Therefore, the selection of Porto and Cagliari reflects a comparative research design aimed at testing the applicability of the proposed framework across distinct yet comparable urban contexts. Both cities are medium-sized European port cities characterised by compact urban forms and historically layered street networks, but differ in terms of transport system development and morphology–transit alignment. This contrast enables the analysis to capture both aligned and misaligned conditions, thereby strengthening the interpretative value of the results.

The paper is structured as follows: Section 2 reviews literature on port-city interfaces, space syntax, and transport equity. Section 3 outlines the methodology. Section 4 presents the spatial, demographic, and statistical results. Section 5 discusses implications for inclusive planning, and Section 6 concludes.

2. Theoretical background

2.1. Transit accessibility and transport equity

Transit accessibility is a central determinant of urban liveability, shaping how residents reach employment, education, healthcare, and other essential opportunities (Te Brömmelstroet et al., 2022). In most cities, accessibility is operationalised through the spatial relationship between population distribution and the public transport network, with walking catchments around stops commonly used to approximate service availability at neighbourhood scale (Jain & Tiwari, 2021). Such measures provide a straightforward way to identify areas that remain disconnected despite being embedded within otherwise well-served urban fabrics. Equity concerns emerge when disparities in transit access disproportionately affect population groups with higher mobility needs. Studies consistently show that children, older adults, and low-income residents face heightened vulnerability when forced to rely on longer walking distances, poorly connected street networks, or neighbourhoods with limited transit coverage (Páez et al., 2010; Allen & Farber, 2021). Recent work highlights that accessibility gaps often arise not only from the distribution of stops but also from settlement patterns and urban form, which condition how different groups experience the public transport system (Manaugh & El-Geneidy, 2012; Golub et al., 2019).

Despite these advances, accessibility analysis still tends to conceptualise transit provision independently of the structural logic of the street network. This separation limits the ability to understand where transit infrastructure reinforces or undermines the movement potential embedded within the urban fabric. Addressing equity therefore requires diagnostic approaches that integrate demographic exposure with the spatial structure of transport and street networks, enabling planners to detect misalignments that may contribute to uneven accessibility outcomes.

2.2. Configurational centrality and urban movement structure

The spatial configuration of the street network exerts a strong influence on how people move through cities, shaping both everyday mobility patterns and the distribution of urban activities. Space syntax research has demonstrated that the structural properties of street networks—particularly the degree to which segments integrate into wider patterns of connectivity—generate predictable movement flows independent of land-use characteristics (Hillier et al., 1984; Hillier, 1996). Streets that are more centrally embedded within the network tend to attract higher pedestrian volumes, greater commercial activity, and enhanced urban vitality, reflecting the city's underlying movement potential (Karimi, 2023; Cutini, 2025).

These configurational measures provide an effective way to capture the macro-scale accessibility offered by the street system itself. Normalised angular integration (NAIN), for example, reflects how efficiently a street segment connects to all others in angular terms, offering a scale-independent indicator of structural centrality (Arcaute & Ramasco, 2022). Because centrality shapes pedestrian catchments and influences route choices, it offers a relevant lens for examining transport provision: transit systems that align with the configurational hierarchy tend to amplify inherent accessibility, while those that diverge may generate avoidable gaps in service effectiveness (Curtis & Scheurer, 2016). In this study, centrality is not interpreted as a proxy for travel demand but as an indicator of the city's potential to support efficient transit access. This approach enables a diagnostic comparison between the structural logic of the street network and the distribution of public transport stops, providing insight into where morphological conditions facilitate or constrain accessible mobility within evolving port-city contexts. While Angular Segment Analysis (ASA) provides a robust and widely validated framework for capturing configurational centrality, it is important to acknowledge its analytical boundaries. ASA abstracts movement potential from land-use distribution, socio-economic factors, and behavioural variability, focusing instead on the structural properties of the street network. As such, it does not directly account for modal preferences, service frequency, or temporal variations in transport systems.

Additionally, high integration does not necessarily imply high demand in all contexts, particularly in areas where functional attractors are weak or where physical constraints such as topography or infrastructure barriers limit accessibility. These limitations suggest that ASA should be interpreted not as a predictor of actual movement, but as an indicator of latent spatial potential that may or may not be realised depending on planning decisions. In this study, ASA is therefore employed as a diagnostic baseline against which the effectiveness of transit provision can be evaluated. By comparing configurational centrality with observed transit coverage, the analysis identifies whether transport systems reinforce or neglect the underlying spatial logic of the urban network. Beyond its role as an analytical technique, space syntax constitutes a theoretical framework for understanding how spatial configuration structures movement patterns and urban activity. A central concept within this framework is Hillier's notion of the "dual-structure city", which distinguishes between the configurational structure of the street network and the distribution of functional land uses. The configurational structure defines the underlying movement potential of the city, while land-use patterns respond to and reinforce this structure over time.

Within this perspective, highly integrated streets are not merely geometrically central but form part of a movement-based urban skeleton that organises accessibility, encounter, and economic activity. This distinction is particularly relevant for transport planning: while transit systems are often designed based on operational or infrastructural constraints, their effectiveness depends on how well they align with this underlying configurational structure. The present study builds on this theoretical foundation by interpreting configurational centrality as a representation of latent movement potential and by assessing whether transit provision reinforces or diverges from this structure. In doing so, the analysis bridges the theoretical insights of space syntax with applied diagnostics of transport accessibility, extending its relevance to contemporary planning contexts.

2.3. Linking urban form, transit provision, and spatial equity

Building on the preceding discussion of transit accessibility and configurational centrality, this section synthesises how urban form mediates the relationship between spatial structure, transport provision, and equity outcomes. Configurational analyses grounded in space syntax demonstrate that street networks possess an inherent hierarchy that channels pedestrian flows and concentrates activity along structurally high-integration corridors (Hillier et al., 1984; Hillier, 1996; Karimi, 2023). When transit provision aligns with these centrality patterns, public transport can efficiently leverage the city's intrinsic movement structure; when misaligned, even dense networks may fail to deliver meaningful accessibility (Oliveira, 2016; Cutini, 2025). Recent work in urban analytics similarly shows that morphological coherence supports higher transit use and that gaps often emerge where network geometry, land-use distribution, and service supply diverge (Boix et al., 2011; Arcaute et al., 2016).

These dynamics become particularly pronounced in specific urban contexts where spatial restructuring is ongoing. For example, in port cities undergoing waterfront redevelopment, shifts in land use, activity patterns, and movement flows can intensify the consequences of alignment or misalignment between street-network configuration and transit provision (Curtis & Scheurer, 2016). In such contexts, assessing whether transit infrastructure follows the logic of the street network is essential for identifying spatial mismatches that may intensify inequities for groups with limited mobility flexibility.

Integrating configurational measures with transit coverage and demographic exposure therefore provides a more robust diagnostic basis for understanding accessibility outcomes. By examining how inherent movement potentials intersect with service availability and population vulnerability, it becomes possible to detect where planning decisions reinforce or contradict the structural capacities of the urban fabric. Such integrated approaches are particularly valuable in medium-sized cities, where small shifts in transit alignment can produce disproportionate accessibility impacts. The framework also contributes to ongoing debates on proximity-based planning models, particularly the "15-min city" paradigm, which emphasises equitable access to essential services within short travel distances. While much of this discourse focuses on land-use mix and local service provision, less attention has been given to the role of street-network configuration and its interaction with public transport systems.

From a configurational perspective, the effectiveness of proximity-based planning depends not only on the spatial distribution of services but also on whether structurally central corridors are supported by efficient mobility networks. Misalignment between transit provision and high-integration streets may undermine the practical realisation of proximity ideals, even in compact urban settings. In this sense, the morphology–transit alignment approach proposed in this study offers a complementary diagnostic tool for evaluating the spatial coherence of 15-min city strategies, particularly in historically layered and infrastructure-constrained urban environments. Overall, this integrated perspective emphasises that spatial equity is not solely a function of transport supply or demographic distribution, but emerges from the interaction between urban morphology, movement structure, and service provision. This conceptual linkage provides the foundation for the diagnostic framework developed in this study.

2.4. Study area context

Porto (Portugal) and Cagliari (Italy) are medium-sized Southern European port cities whose compact centres, historic street patterns, and ongoing waterfront transformations provide an appropriate context for examining how transit provision aligns with underlying movement structures (Fig. 1). Both cities exhibit spatial configurations in which accessibility outcomes depend on the interaction between urban morphology and surface public transport networks, a dynamic commonly observed in Mediterranean port cities undergoing redevelopment (Curtis & Scheurer, 2016; Fulton et al., 2017).

Porto's urban form is shaped by a polycentric and topographically complex structure extending from its medieval core toward the Atlantic waterfront. The city's bus and metro systems operate along a combination of radial and circumferential corridors, with recent service adjustments responding to redevelopment pressures along the riverfront and former industrial areas. These conditions generate heterogeneous transit coverage, particularly where emerging attractors fall outside established network axes. The resulting street–network relationships reflect broader findings on how configurational hierarchy influences movement and accessibility in uneven terrains (Karimi, 2023; Oliveira, 2016).

Cagliari presents a more monocentric and radially organised layout centred on its historic core and port basin. The bus network functions as the primary public transport system, extending along major radial routes but with limited penetration into highly central local grids. Recent waterfront interventions have intensified demand for enhanced connectivity between consolidated neighbourhoods and newly activated port-edge spaces, reflecting patterns observed in other small-to-medium port cities undergoing spatial reconfiguration (Curtis & Scheurer, 2016). The administrative extent used for Cagliari corresponds to the Metropolitan City of Cagliari, comprising 17 municipalities, and reflects the official territorial configuration valid until June 2025.

Despite differences in scale, morphology, and network geometry, both cities share a common planning challenge: ensuring that transit provision reinforces rather than contradicts the structural centrality embedded within the street network. Their contrasting conditions make

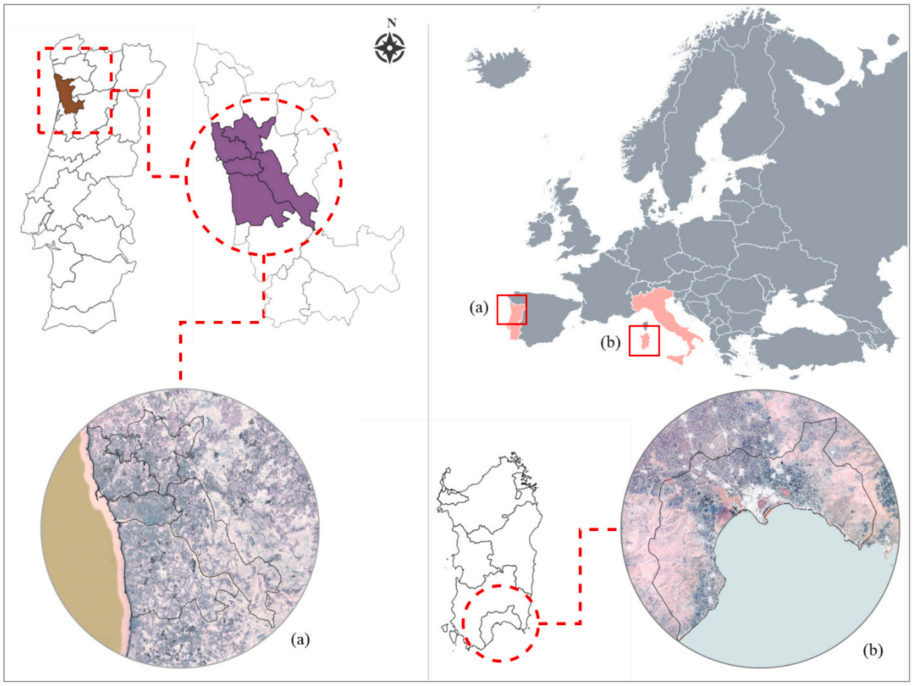

Fig. 1. Geographical location of (a) Porto metropolitan area municipalities, and (b) Cagliari metropolitan areas.

them suitable cases for testing the transferability of an integrated morphology–transit diagnostic framework and assessing whether misalignments disproportionately affect population groups (Table 1) with higher mobility needs.

3. Data sources and research methods

3.1. Data sources and preparation

The methodological framework integrates spatial network analysis, public transport coverage mapping, and demographic overlays to quantify accessibility mismatches in port–city interfaces. The objective is to evaluate whether morphologically high-integration corridors of the street network are adequately supported by transit services, and to assess the degree to which this alignment (or misalignment) affects vulnerable population groups. The comparative approach adopted in this study is essential to evaluate the robustness and transferability of the proposed diagnostic framework. While a single-case analysis could identify patterns of accessibility within a specific context, it would not allow for assessment of how morphology–transit alignment varies across different urban conditions. By examining two cities with shared structural characteristics but differing transport configurations, the study is able to distinguish between context-specific outcomes and more generalisable patterns of alignment and misalignment. This enhances the explanatory depth of the analysis and supports the broader applicability of the proposed indicators.

Table 1
Study area demographics.

Metropolitan area	Included municipalities	Total study area population	Key characteristics
Porto	5 (Core municipalities)	~891,153	Includes the historic core (Porto) and key port-related municipalities.
Cagliari	17 (Full metropolitan area)	~421,041	Encompasses the entire metropolitan region, providing a comprehensive view.

Note: The Cagliari study area corresponds to the Metropolitan City of Cagliari administrative boundary (17 municipalities), as defined in the official territorial configuration valid until June 2025.

The analysis was carried out in four main stages:

1. Data acquisition and preparation;
2. Global integration analysis using space syntax;
3. Public transport coverage mapping;
4. Demographic overlay and Equity Assessment;
5. Statistical validation.

A consistent analytical workflow was applied to both Porto and Cagliari to ensure methodological comparability (Fig. 2).

The analysis draws on multiple datasets covering street networks, public transport infrastructure, and demographic characteristics for both Porto and Cagliari. All datasets were selected to ensure completeness, spatial accuracy, and temporal relevance to the study period (2021–2025).

Street network shapefiles for Porto and Cagliari were obtained from OpenStreetMap (OSM, May, 2025). Data were downloaded in shapefile format using the Geofabrik export service to ensure coverage of the entire municipal boundary, including port-adjacent areas and peripheral districts connected to the waterfront. Transit stop location data were acquired from the official public transport operators in each city. For Porto, stops were extracted from the STCP – Sociedade de Transportes Colectivos do Porto GTFS feed (STCP, May, 2025), which provides real-time and static stop coordinates. For Cagliari, data were obtained from the CTM – Consorzio Trasporti e Mobilità GTFS feed (CTM, May, 2025). Only active transit stops serving scheduled routes during the study period were retained. Duplicated stops within 5 m of each other (e.g., opposite-direction stops mapped separately) were consolidated to avoid double counting in coverage analysis.

Population data were sourced from the most recent national censuses for each country, Instituto Nacional de Estatística (INE, 2021) for Porto and Istituto Nazionale di Statistica (ISTAT, 2021) for Cagliari. Census counts were obtained at the smallest publicly available spatial unit, census subsections for Portugal and sezioni di censimento for Italy, enabling fine-grained demographic mapping. In Porto, demographic

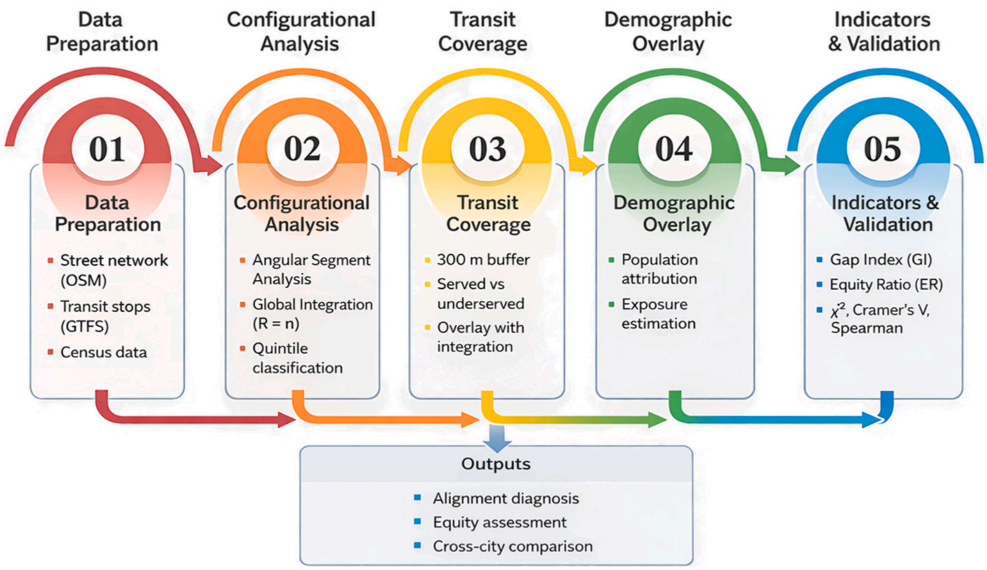

Fig. 2. Proposed methodological framework for the study.

data were obtained at the level of BGRI subsections, the smallest census units defined by Statistics Portugal (INE), comparable to census tracts. For each unit, total population counts and age-specific counts for children (<14 years) and senior citizens (>65 years) were extracted. These attributes were then linked to their respective spatial polygon boundaries to generate demographic layers for each city. Datasets were harmonised into consistent spatial projections for each city. However, the analysis extent was defined by the official municipal boundary of each city, supplemented with contiguous built-up areas directly linked to the port–city interface. All datasets were clipped to these boundaries to focus on the urban system relevant to port accessibility.

All datasets were selected to ensure completeness, spatial accuracy, and temporal consistency, combining census data from 2021 with transport and network datasets updated to 2025. Datasets were validated against aerial imagery and operator maps to ensure completeness and accuracy. The result was a harmonised geospatial database for each city, comprising:

- A cleaned, pedestrian-accessible street network for space syntax analysis;
- A verified transit stop layer for coverage assessment;
- Census polygons with population attributes for total, children, and seniors.

3.2. Global integration analysis (R = n)

Following data preparation, the cleaned pedestrian-accessible street networks for Porto and Cagliari were processed to calculate global integration values using the segment analysis approach within the DepthmapX platform. Segment maps were generated from the OSM-derived street centreline shapefiles by automatically splitting each axial line at intersections, ensuring that each segment represents the smallest navigable unit of the network. The analysis was set to radius = n, which considers the shortest topological path between each segment and all others in the network. This produces a measure of structural centrality that captures the overall integration of each segment within the city's street system. Higher values indicate segments that are, on average, fewer steps away from all other segments, and therefore more likely to support through movement at the citywide scale.

Integration results were normalised for comparability between cities. The output integration maps were exported as attribute-enriched shapefiles and imported into GIS for further processing. Integration values were classified into quintiles to produce a clear visual hierarchy of street centrality, with the highest quintile representing the most integrated corridors. This classification was retained for later overlays with transit coverage and demographic data, enabling consistent interpretation across all subsequent analytical stages.

3.3. Public transport coverage analysis

The verified transit stop point datasets (STCP for Porto, CTM for Cagliari) were used to model the pedestrian catchment area of each transit stop. The analytical workflow was designed to be transferable and replicable across cities with minimal data requirements. All analytical steps rely exclusively on openly available datasets: street networks from OSM, transit stop locations from GTFS feeds, and population data from national census sources. These inputs allow the method to be applied in data-limited settings while ensuring consistency across diverse urban contexts. The workflow does not depend on city-specific parameters or calibration, making it suitable for comparative studies and scalable for municipal auditing purposes. Determination of which street segments fell inside (covered) or outside (uncovered) the service area enabled the categorisation of integration results into two functional classes:

1. Integrated but underserved corridors – high-integration segments located outside the coverage polygon.
2. Transit-rich but weakly integrated corridors – low-integration segments located inside the coverage polygon.

This classification was performed using an attribute join between the integration shapefile and the buffer coverage layer, allowing direct spatial queries on integration value thresholds relative to transit stop coverage. The choice of a 300 m walking threshold follows established proximity-based accessibility metrics commonly used in European urban transport diagnostics. This threshold provides a conservative, policy-relevant reference that is appropriate for cross-city comparison. While this study applies a fixed 300 m Euclidean radius for consistency, the framework is fully extensible to alternative thresholds (e.g., 250 m or 400 m) without altering the underlying analytical logic. The analysis focuses exclusively on bus-based public transport systems in both cities, as these represent the most spatially extensive and consistently available mode across the study areas. However, other modes such as metro and rail systems, particularly in Porto, are not included in the coverage assessment. This may lead to an underestimation of total transit accessibility and should be considered when interpreting the results.

3.4. Demographic overlay and equity assessment

The final stage links public transport accessibility with population distribution to evaluate equity outcomes. Demographic indicators considered include total population, children under 14, and seniors over 65, selected for their relevance to mobility vulnerability and transport justice. These indicators were derived from national statistical sources at the commune level in Cagliari and at the BGRI subsection level in Porto.

High-integration streets were classified as served or underserved, and population exposure estimated accordingly. In Cagliari, underserved shares of high-integration street length (U_s) were applied proportionally to commune-level population counts. In Porto, the merged dataset allowed direct attribution of residents to BGRIs flagged as underserved.

Population exposure was estimated as:

$$P_g^{und} = U_s \times P_g \tag{1}$$

$$P_g^{srv} = (1 - U_s) \times P_g \tag{2}$$

where P_g is the total population of group, P_g^{und} is the underserved population, and P_g^{srv} is the well served population;

Two indices were derived:

- Gap Index (GI): the percentage of a group estimated to live in underserved areas,

$$GI_g = \frac{P_g^{und}}{P_g} \times 100\% \tag{3}$$

- Equity Ratio (ER): the ratio of served to underserved population for each group,

$$ER_g = \frac{P_g^{und}}{P_g^{srv}} \tag{4}$$

The Gap Index quantifies the magnitude of exposure to accessibility deficits, while the Equity Ratio evaluates the relative balance between served and underserved populations. Consider, ER > 1 indicates equitable over-provision; ER = ∞ represents optimal alignment; ER ≈ 1 signals systemic deficit. The Gap Index (GI) and Equity Ratio (ER) are conceptualised as composite indicators grounded in established approaches to accessibility and transport equity assessment. Specifically, GI builds on proximity-based accessibility measures that quantify the share of population lacking access to transport services within defined thresholds, while ER reflects ratio-based equity metrics commonly used to evaluate disparities between served and underserved populations. Rather than introducing entirely new constructs, the contribution of these indicators lies in their integration with configurational centrality derived from space syntax. This combination enables a novel diagnostic perspective that captures whether transit provision aligns with the inherent movement structure of the street network. In this sense, GI and ER function as operational tools for evaluating morphology–transit alignment, extending existing accessibility metrics into a configurational framework.

It is important to note that the proportional allocation applied in Cagliari assumes an even distribution of population relative to the length of high-integration street segments within each commune. This abstraction does not account for intra-communal variations in land use, residential density, or building typology, and may therefore introduce aggregation bias. Highly integrated corridors may include commercial or mixed-use areas with limited residential presence, meaning that population exposure may be over- or under-estimated in specific locations.

This limitation reflects differences in data resolution between the two case studies: while Porto allows direct attribution at the BGRI level, equivalent fine-grained demographic data were not available for Cagliari. The approach adopted here should therefore be interpreted as an estimation of relative exposure patterns rather than precise population counts. Despite this limitation, the analysis remains robust at the structural level, as the identification of underserved high-integration corridors is independent of demographic allocation. The proportional method is used solely to approximate the distributional implications of this structural misalignment. Accordingly, cross-city comparisons are interpreted in terms of systemic morphology–transit alignment rather than strictly equivalent demographic precision.

3.5. Statistical validation

Statistical validation was conducted to determine if the observed links between network integration and transit provision were systematic rather than accidental. Integration values were categorised into quintiles (Q1–Q5), with Q1 denoting the lowest 20% of integrated streets and Q5 indicating the highest 20%. Each quintile categorised streets as serviced (within 300 m of a transportation station) or underserved. A 5 × 2 contingency table was generated and evaluated using the chi-square test of independence, with Cramer's V given as the effect size. Simultaneously, Spearman's rank correlation between continuous integration values and binary service status was calculated. These approaches enable the evaluation of important association between transit coverage and morphological centrality.

Integration values I_i for each street segment i were ordered and divided into five equally sized groups (Q1–Q5). Each quintile contains 20% of the distribution:

$$Q_k = \{I_i : p_k - 1 < \text{rank}\,(I_i) \le p_k\}, k = 1, \ldots, 5 \tag{5}$$

where p_k are the 20%, 40%, …, 100% percentiles.

The following was computed to evaluate if the state of service (served/underserved) was unrelated to the integration quintile:

$$\chi^2 = \sum_{r=1}^{5} \sum_{c=1}^{2} \frac{(O_{rc} - E_{rc})^2}{E_{rc}} \tag{6}$$

where O_{rc} are observed counts and E_{rc} are expected counts under Independence.

Effect size or Cramer's V can be defined as follows:

$$V = \sqrt{\frac{\chi^2}{N \times (k-1)}} \tag{7}$$

where N is the sample size and $k = \min$ (rows, columns).

A rank-based correlation between integration values and service status was also calculated:

$$\rho = 1 - \frac{6 \sum d_i^2}{n\,(n^2 - 1)} \tag{8}$$

where d_i is the difference in ranks between integration I_i and service status S_i, and n is the number of observations.

However, this study adopts a simplified measure of accessibility defined as proximity to transit stops within 300 m (considering it as the minimum walking distance). While this measure does not capture network-based walking distances, service frequencies, or travel times, it provides a consistent, transferable benchmark that can be applied across cities with varying data availability. The aim is not to reproduce detailed travel behaviour but to evaluate the alignment between morphological centrality and basic transit coverage in port–city contexts.

4. Results and analysis

4.1. Network integration patterns

In Porto, high integration concentrates in the Baixa district and extends along axial corridors parallel to the Douro River. These segments intersect with several of the city's densest residential neighbourhoods, meaning that a substantial share of the population including children and seniors resides adjacent to high-integration corridors (Fig. 3). This suggests that vulnerable groups already benefit from strong morphological accessibility. However, steep topography produces pockets of low integration in elevated peripheral areas, indicating that physical barriers may constrain how these residents reach the city's structural arteries.

Cagliari displays a more radial hierarchy, with integration values emanating from the Castello district and converging on the waterfront. While total population density overlaps with these integrated axes, the demographic overlays show a more uneven pattern: children are relatively well distributed along central streets, whereas many seniors occupy peripheral areas with lower integration (Fig. 3). This indicates that older residents may face heightened mobility barriers despite the city's compact structure.

4.2. Transit stop coverage of high-integration corridors

Overlaying transit stop catchments with high-integration corridors reveals strong reinforcement in Porto and substantial gaps in Cagliari. In Porto, every highly integrated segment lies within 300 m of at least one stop. Coverage extends from the Baixa and Ribeira waterfront into surrounding neighbourhoods, producing virtually no identifiable underserved corridors. Transit provision therefore fully supports the structural backbone of the urban fabric. In Cagliari, the pattern diverges sharply. Approximately 47.8% of high-integration corridors fall outside 300 m stop buffers, leaving nearly half of the city's structurally central network underserved. Several key radial connectors between Castello, the waterfront, and outer districts remain beyond walking distance of transit. This indicates that the transit system does not consistently service the very corridors with the greatest movement potential. The detailed views reinforce this contrast (Fig. 4). In Porto, stops cluster tightly along integrated waterfront streets, creating a seamless interface between central districts and transit. In Cagliari, many port-adjacent radial axes, despite being highly integrated, remain unserved, illustrating a persistent disconnect between street centrality and transit routing.

4.3. Demographic exposure and equity outcomes

The contrasting morphological–transit relationships result in

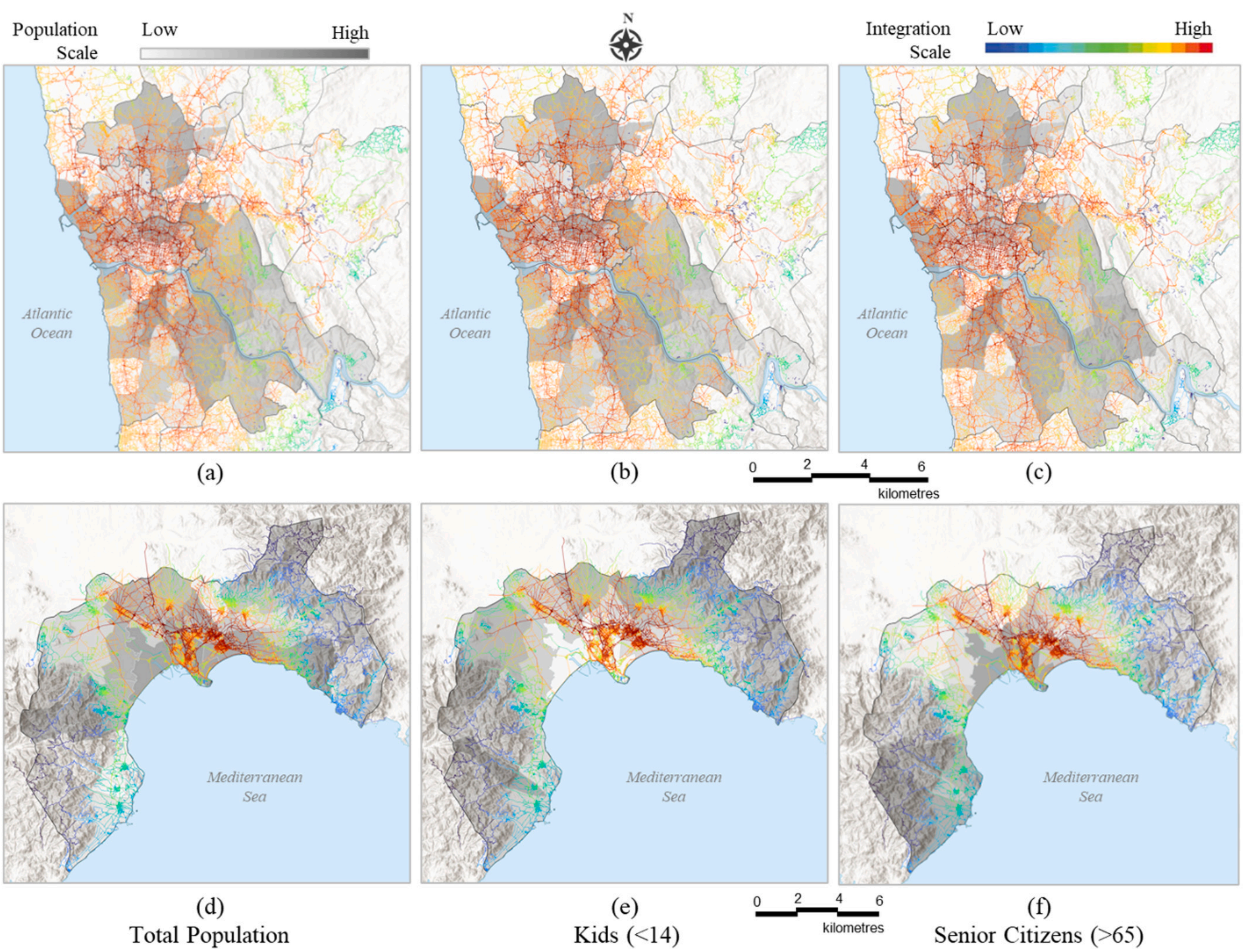

Fig. 3. Global integration (R = n) results overlaid with demographic distributions for total population, children (<14), and seniors (>65) in Porto (top row) and Cagliari (bottom row).

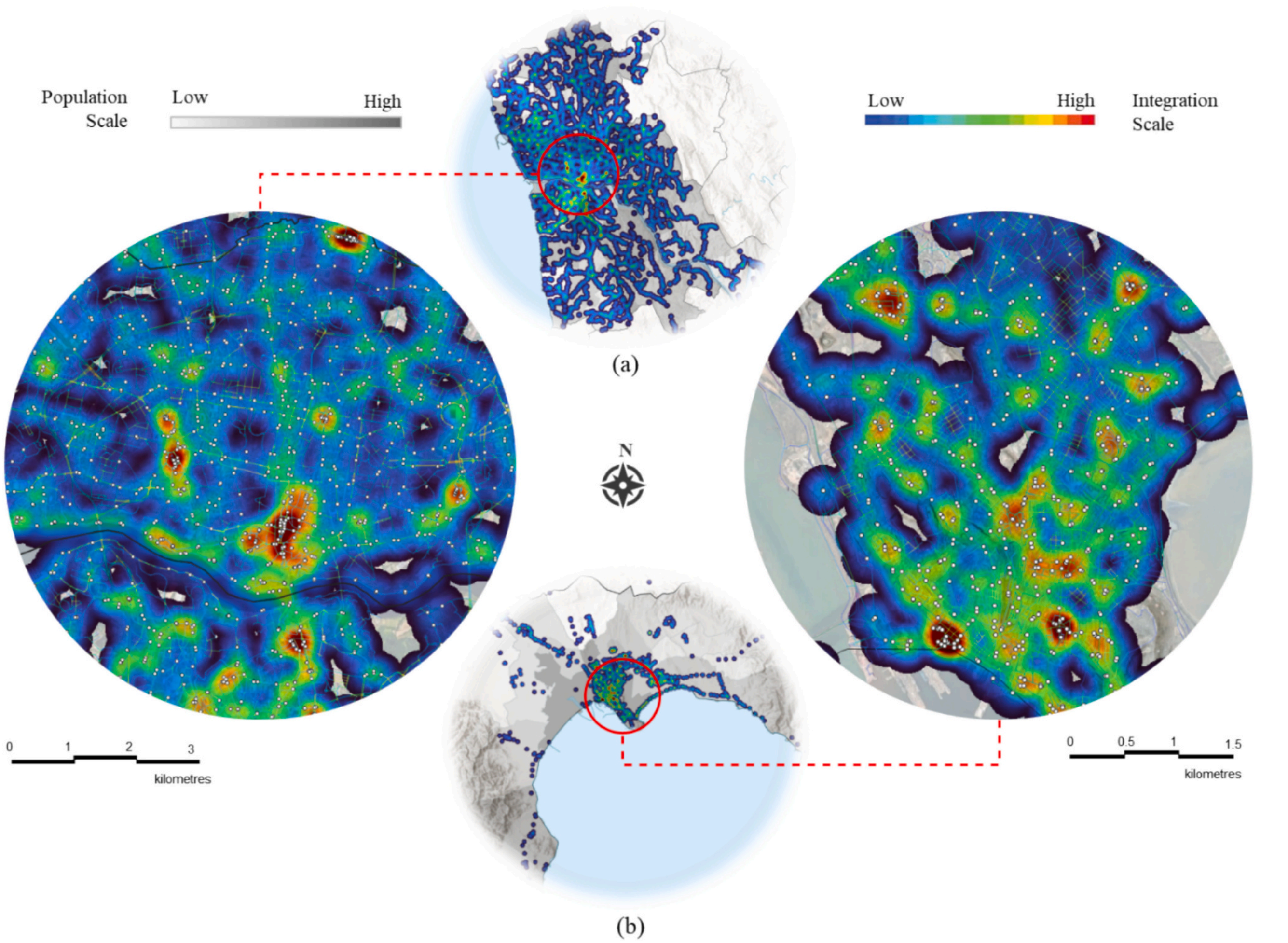

Fig. 4. Closer views of transit stop coverage in the central districts of (a) Porto and (b) Cagliari, highlighting the contrasting alignment of transit stops with highly integrated port-adjacent streets.

fundamentally different equity outcomes. Porto exhibits complete reinforcement of its street hierarchy, producing zero exposure for all demographic groups. Children, seniors and the total population are equally well served, indicating that transit provision neutralises the constraints imposed by topography and ensures equitable access along high-integration corridors (Fig. 5).

Because no underserved segments were present in Porto, statistical tests would not yield meaningful associations. In Cagliari, population exposure was estimated proportionally because underserved segments were present; in Porto, no underserved segments existed. The overlays confirm that underserved high-integration corridors occur not only in outer districts but also along port-adjacent radial axes, where transit support should ideally be strongest (Fig. 5). This indicates that equity challenges stem from a misalignment between network geometry and transit routing rather than uneven demographic distribution.

Communal differences reinforce this interpretation: while Cagliari city and Selargius account for the largest absolute shares of underserved residents due to their population size, smaller communes show comparable proportional exposure (Table 2). This confirms that the accessibility gap permeates the metropolitan area rather than concentrating demographic or geographic clusters. In Cagliari, the Gap Index (47.8%) and Equity Ratio (1.09) are identical across all demographic groups. This uniformity is a direct consequence of the proportional allocation method, which distributes underserved exposure evenly across population categories. Rather than indicating differentiated impacts, this result points to a systemic accessibility deficit embedded in the spatial configuration of the transit network, affecting all groups irrespective of their demographic characteristics. It reinforces that the observed inequity arises primarily from morphology–transit misalignment rather than from uneven demographic distribution.

4.4. Statistical association between street integration and transit coverage

Porto showed complete alignment between structural centrality and transit provision, with all segments in quintiles Q1–Q5 lying within 300 m of a stop. This produced a GI of 0% and an ER approaching infinity across all groups; statistical tests were therefore not applicable.

In Cagliari, underserved segments occurred in every quintile, although disproportionately in the highest-integration class (Q5), where 46.2% of streets lacked stop coverage (Table 3). The chi-square test indicated a statistically significant association between integration and transit service ($\chi^2(4) = 238$, $p < 0.001$). The effect size (Cramer's V = 0.14) and correlation coefficient (Spearman $\rho = -0.11$, $p < 0.001$) suggest a weak-to-moderate relationship: more integrated streets were somewhat more likely to be underserved. The weak negative correlation also reflects that Cagliari's most integrated streets paradoxically lack transit, confirming a planning-network misalignment. This pattern may reflect historical path dependencies. Many of the most integrated streets in Cagliari originate from the premodern pedestrian network, whereas bus routes have evolved along wider modern arterials. The resulting divergence between historical street logic and transit planning helps explain why structurally high-integration corridors remain insufficiently serviced. It should be noted that population exposure estimates for Cagliari are derived from proportional allocation and should therefore

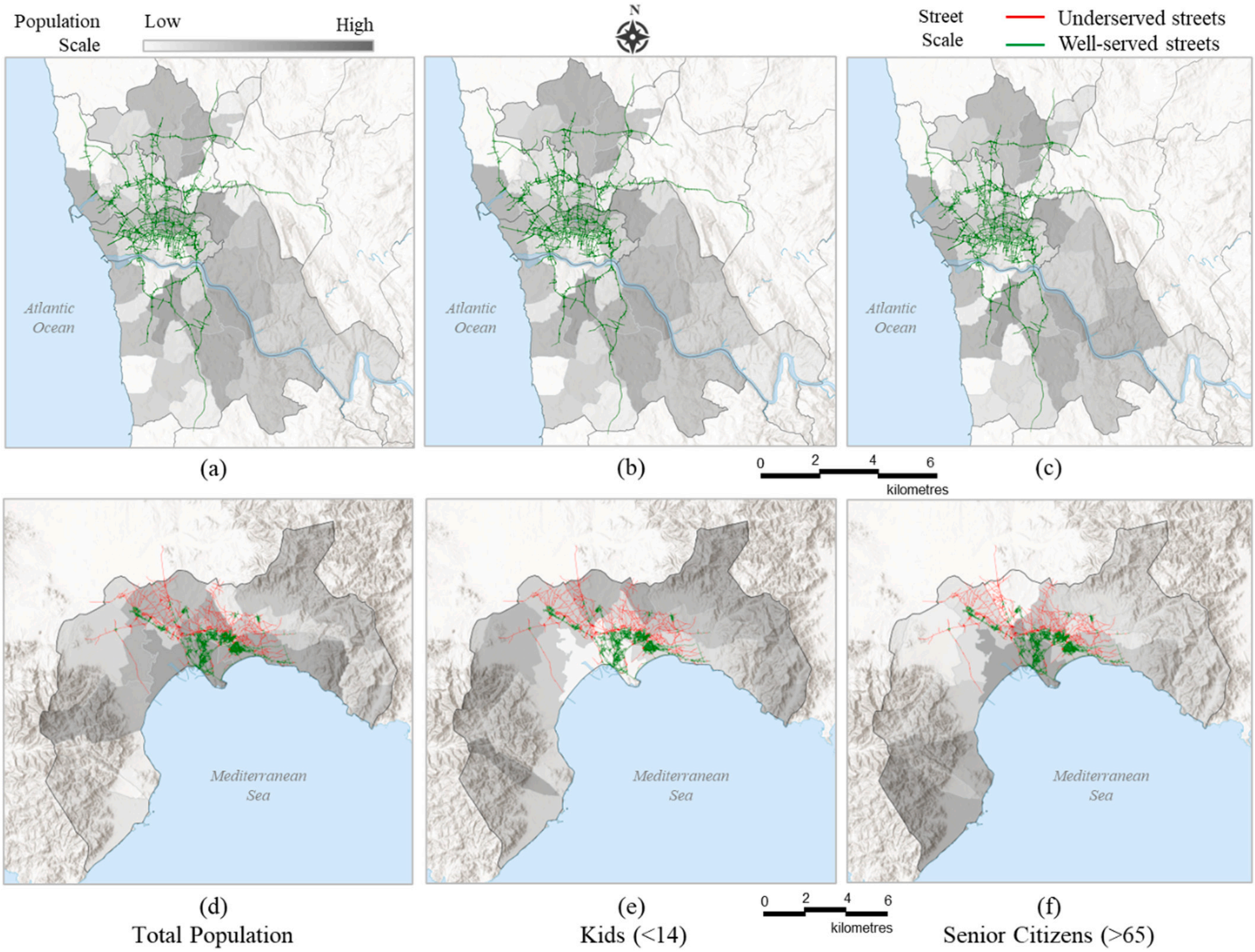

Fig. 5. Demographic exposure to transit stop coverage of high-integration corridors in Porto (top row) and Cagliari (bottom row) for total population, children (<14), and seniors (>65). Green indicates well-served high-integration corridors; red denotes underserved corridors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Overall exposure outcomes for Porto and Cagliari.

Metropolitan areas	Demographic group	Population	Served	Underserved	*GI* (%)	*ER*	Remarks
Porto	Total population	891,153	891,153	0	0.0	∞	All high-integration corridors within transit stop coverage; no population exposure.
	Children (<14)	115,850	115,850	0	0.0	∞	Equitable coverage across age groups.
	Seniors (>65)	208,530	208,530	0	0.0	∞	No demographic disparities.
Cagliari	Total population	421,688	220,121	201,567	47.8	1.09	Nearly half of population exposed to underserved high-integration corridors.
	Children (<14)	71,439	37,291	34,148	47.8	1.09	Exposure affects children equally, indicating structural misalignment.
	Seniors (>65)	155,132	80,979	74,153	47.8	1.09	Seniors face systemic underserved exposure.

Note: Identical GI and ER values across demographic groups in Cagliari reflect proportional allocation and indicate uniform exposure patterns.

be interpreted as indicative of relative patterns rather than precise spatial distributions of demographic groups.

5. Discussion

The results illustrate a sharp divergence in how Porto and Cagliari's transit systems interact with the structural logic of their street networks, revealing fundamental differences in transport equity within port–city contexts. Porto represents an optimal case in which transit routing fully reinforces configurational centrality: all high-integration corridors fall within 300 m of at least one transit stop, yielding a Gap Index (GI) of 0% and an Equity Ratio (ER) approaching infinity. No demographic group—total population, children, or seniors—is exposed to underserved conditions, indicating a complete absence of proximity-based accessibility gaps. This study set out to examine the extent to which public transport provision aligns with configurationally central corridors and how such alignment influences population exposure to accessibility deficits. The findings provide a clear answer to this question by demonstrating two contrasting conditions: in Porto, transit provision closely follows the configurational structure of the street network,

Table 3
Statistical estimations for the quantiles and validations.

Statistical estimations based on quintiles of the study areas

City	Quintile	Underserved	Served	% Underserved	Notes
Porto	Q1–Q5	0	100%	0%	Complete coverage
Stats	–	–	–	–	$GI = 0\%$; $ER \rightarrow \infty$; tests not applicable
Cagliari	Q1	731	1688	30.2%	–
	Q2	713	1706	29.5%	–
	Q3	696	1724	28.8%	–
	Q4	739	1679	30.6%	–
	Q5	1117	1302	46.2%	Highest imbalance
Stats	–	–	–	–	$\chi^2(4) = 238$, $p < 0.001$; $V = 0.14$; $\rho = -0.11$ ($p < 0.001$)

Statistical association between integration and transit coverage

City	χ^2 (df)	*p*-value	Cramer's V	Spearman ρ	Interpretation
Porto	–	–	–	–	Full alignment; test not applicable
Cagliari	238 (4)	<0.001	0.14	−0.11	Weak but significant misalignment

resulting in negligible exposure, whereas in Cagliari, a significant misalignment leads to widespread and structurally embedded accessibility deficits. In Cagliari, the Gap Index (47.8%) and Equity Ratio (1.09) are identical across all demographic groups. This uniformity reflects the proportional allocation approach and indicates that exposure to underserved high-integration corridors is systemic rather than group-specific. Rather than revealing differentiated impacts, the results demonstrate that the misalignment between transit provision and street-network configuration generates a citywide accessibility deficit affecting all population groups equally.

These findings are consistent with existing research that highlights the importance of spatial configuration in shaping movement patterns and accessibility outcomes. Previous studies in space syntax have demonstrated that highly integrated streets form the backbone of urban movement systems, attracting flows and activities. However, transport accessibility research has often evaluated service provision independently of this configurational structure, focusing instead on proximity or service frequency. The present study bridges this gap by showing that accessibility outcomes are not only a function of distance to transit, but also of whether transit systems align with the underlying spatial logic of the urban network. In this sense, the results extend existing approaches by introducing morphology–transit alignment as a critical dimension of accessibility analysis. From a theoretical and methodological perspective, the study contributes to the literature by integrating configurational centrality with population-based exposure metrics. This combination enables a more nuanced understanding of accessibility, moving beyond traditional measures to capture structural mismatches between urban form and transport provision. The findings suggest that even in relatively compact urban environments, accessibility deficits can persist when transit systems do not reinforce the movement structure defined by the street network.

Interpreting these contrasting outcomes through the existing literature clarifies the systemic nature of Cagliari's deficit. While the magnitude of population exposure in Cagliari should be interpreted with caution due to aggregation effects, the presence and spatial distribution of underserved high-integration corridors remain unaffected by this limitation. Research consistently demonstrates that transit networks often fail to align with the morphological backbone of cities, producing accessibility "misfits" where high-integration corridors remain insufficiently serviced (Lebendiger & Lerman, 2019). These mismatches are not isolated anomalies; systematic reviews of transit equity demonstrate that misalignment between the built environment and transit infrastructure is a widespread phenomenon, one that contributes to persistent inequalities and spatially entrenched disadvantage (Wan et al., 2023). In this context, Cagliari's pattern—where nearly half of structurally high-integration corridors lack coverage—is characteristic of a broader, well-documented planning failure.

Porto, on the other hand, emerges as an exceptional benchmark. Its complete morphological–transit alignment is unusual, especially given the topographic constraints of its steep valley system and historic core. Porto demonstrates that equitable accessibility is not solely a function of network density; instead, it depends on strategically integrating transit services with the intrinsic centrality of the street network. In doing so, Porto exemplifies how coordinated planning can mitigate the disadvantages created by challenging terrain, decentralised population distribution, or heritage-constrained street geometries. The complete absence of underserved high-integration corridors in Porto was confirmed through manual verification of stop locations and municipal network boundaries to ensure that the result reflected genuine system alignment rather than a data artefact.

These findings also acquire additional significance when interpreted considering contemporary port–city redevelopment. Waterfront transformation strategies often prioritise architectural, cultural, or economic interventions, yet their success is frequently undermined by insufficient mobility integration (Carta et al., 2025). In Porto, the full 300 m coverage across high-integration corridors suggests that transit planning has been effectively synchronised with urban morphological constraints, ensuring that waterfront areas remain strongly connected to the urban hinterland. While more fine-grained multimodal and temporal analyses would be required to confirm this robustness, the proximity-based alignment offers a strong first-order indication of effective strategic coordination.

Cagliari presents a far more problematic scenario. Despite its compact form and clearly defined radial structure, several of its most integrated port-adjacent corridors remain outside transit catchments. This disconnect not only undermines everyday mobility but also threatens the long-term sustainability of waterfront redevelopment efforts. As Gurzhiy et al. (2021) emphasise, successful port–city integration depends on cohesive multimodal accessibility and coherent linkages between maritime zones and the urban core. The persistent exclusion of Cagliari's high-integration port-edge streets from the transit network directly contradicts these principles, suggesting a structural barrier to equitable regeneration. The observed misalignment in Cagliari is consistent with broader challenges documented in urban mobility planning, where transit networks often evolve along infrastructural or operational constraints rather than in response to the configurational logic of the street network. In port-city contexts, this disconnect is further amplified by the spatial reorganisation associated with waterfront redevelopment, which can introduce new movement demands without corresponding adjustments in transit routing.

Although this study does not incorporate empirical validation through planning documents or user perception data, the findings align with established concerns in municipal mobility strategies regarding last-mile accessibility, uneven service distribution, and the integration of emerging urban districts. Future research could extend the present framework by triangulating configurational diagnostics with policy analysis or user-based accessibility assessments.

5.1. Conceptual and methodological contributions

A central contribution of this study lies in demonstrating the analytical value of coupling configurational centrality with transit coverage and demographic exposure. The Gap Index and Equity Ratio, relying only on open data and simple catchment logic, offer practical and transferable benchmarking tools. By extending space syntax methods into the domain of transport equity, the framework highlights that accessibility is shaped not only by network potential but by the strategic decisions embedded in transit routing. This helps clarify whether equity gaps result from demographic distribution, morphological fragmentation, or planning misalignment. The interpretation aligns with the dual-structure perspective, where the failure of transit systems to align with configurational structure reflects a disconnect between movement networks and functional urban organisation. The comparison between Porto and Cagliari showcases the diagnostic power of the framework. Porto's zero-exposure scenario confirms how well-aligned systems can prevent inequities from forming along high-integration corridors. Conversely, Cagliari's uniform exposure across all demographic categories demonstrates how misalignment creates systemic disadvantage, even where demographic vulnerability is not spatially concentrated. This sheds light on a critical but often under-analysed dimension of transport equity: inequities may emerge from structural deficiencies rather than demographic distribution alone.

5.2. Planning implications

The results carry several implications for urban and mobility planning in port–city contexts:

- Embed morphology–transit alignment into mobility policy: Transit planning should be guided by the inherent logic of street centrality, ensuring that high-integration corridors—particularly those linking historic centres and waterfronts—receive priority in stop siting and route design.
- Strengthen connectivity within waterfront redevelopment: As demonstrated in Porto, reinforcing transit along port-edge corridors can help integrate emerging waterfront districts into the wider urban fabric. Cagliari's gaps illustrate the risks of allowing redevelopment to proceed without adequate mobility foundations.
- Establish municipal monitoring tools: The Gap Index and Equity Ratio can be adopted as lightweight diagnostic indicators for periodically assessing underserved exposure, enabling planners to identify gaps as they evolve.
- Target interventions toward structurally underserved areas: Stop relocation, the addition of feeder services, or the redesign of radial transit axes could substantially reduce exposure in cities like Cagliari, where deficiencies reflect routing choices rather than demographic bias.
- Use morphology-informed diagnostics in resource-constrained settings: The simplicity of the method makes it particularly suitable for small and medium-sized cities that lack advanced modelling capacity but face complex accessibility challenges.

Given the structural nature of the misalignment observed in Cagliari, moderate adjustments to the catchment threshold would not remove the underlying accessibility deficit, although the precise magnitude of exposure would vary.

5.3. Limitations and future research

Several limitations should be acknowledged. The use of 300 m Euclidean buffers provides a transparent approximation of potential pedestrian reach but does not reflect network-based walking paths, slope-induced impedance, or micro-scale barriers. Only bus stops were analysed, omitting metro and tram systems that also influence accessibility in Porto. Demographic exposure was calculated using proportional allocation, which may overlook sub-neighbourhood concentrations of vulnerability. Although sensitivity tests using multiple radii were not conducted, the method can accommodate alternative distance thresholds, which would reposition the magnitude of the Gap Index but not the structural contrast between Porto and Cagliari. Future research could incorporate network-distance measures, slope-adjusted walking models, or multimodal transit layers to refine the analysis. Applying the framework to longitudinal data would allow assessment of how morphological–transit coherence evolves during redevelopment cycles. Additionally, expanding the study to include governance structures or institutional planning trajectories could elucidate how policy decisions shape accessibility outcomes in different port–city contexts.

The comparative analysis of Porto and Cagliari underscores how morphology–transit alignment operates as a decisive mediator of accessibility outcomes in port-city environments. Although both cities share broadly similar morphological logics, their transit systems engage with these logics in markedly different ways. In Porto, transit routing reinforces the spatial structure of the street network, resulting in complete proximity coverage of its highest-integration corridors. In Cagliari, the opposite pattern emerges: a significant portion of high-integration corridors remains beyond walking-distance access to transit stops, producing population-weighted exposure levels that reflect routing choices rather than demographic concentration or morphological constraints. These findings illustrate that even modest misalignments between transit stops and core configurational elements can generate disproportionate accessibility deficits.

The GI and ER clarify these divergences by converting configurational and demographic patterns into interpretable measures of exposure. Their strength lies in their ability to reveal subtle gaps that conventional supply-focused assessments tend to overlook. When considered alongside broader waterfront redevelopment pressures, the indicators draw attention to the need for more morphology-responsive transit planning, especially in cities experiencing fragmented historical growth and evolving mobility demands. While the analysis is based on Euclidean proximity and single-mode transit layers, the consistency of the observed contrast indicates that the core argument, accessibility is highly sensitive to routing alignment with spatial configuration, remains robust. A key limitation of the comparative analysis lies in the difference in demographic data resolution between the two case studies. While Porto allows fine-grained attribution at the BGRI level, population data for Cagliari are available only at the commune scale, requiring proportional allocation. This asymmetry introduces potential aggregation effects and limits the strict comparability of population-based indicators such as the Gap Index and Equity Ratio. Consequently, cross-city comparisons should be interpreted primarily in terms of structural morphology–transit alignment rather than exact equivalence in demographic exposure. These insights have implications not only for transport planning but also for broader debates on spatial equity and proximity-based urban models, where the effectiveness of accessibility strategies depends on the coherence between urban morphology and mobility systems.

6. Conclusion

This study demonstrates how integrating Space Syntax with proximity-based transit analysis and population-weighted exposure metrics provides a coherent and reproducible way to assess morphology–transit alignment in port-city contexts. By combining angular segment analysis with 300 m transit catchments, the framework reveals whether structurally high-integration corridors, the elements that underpin movement potential in urban networks are effectively supported by transit stops serving nearby populations. Because conventional accessibility measures treat transit proximity independently of configurational structure, they overlook exposure-driven misalignments; the combined framework used here reveals precisely these structural gaps.

Applied to Porto and Cagliari, the diagnostic framework exposes a clear divergence in alignment. Porto shows complete proximity coverage of its highest-integration corridors, indicating that transit routing closely follows the underlying spatial configuration of the street network. Cagliari, by contrast, exhibits a substantial proximity deficit, with a significant share of its central network lying outside walking-distance transit access. These results highlight that accessibility differences between the two cities stem less from urban morphology or demographic distribution and more from strategic decisions in transit routing.

The integrated framework can be readily applied to other cities undergoing transit restructuring, morphological change, or waterfront redevelopment. The indicators developed here, the Gap Index and the Equity Ratio, offer planners a transferable, data-efficient means of identifying where transit provision fails to support central urban corridors and where specific population groups experience disproportionate exposure to underserved areas. Rather than replacing detailed operational models, the framework provides an early-stage diagnostic that can precede more intensive planning and investment decisions. Future work can extend this approach by incorporating network-based walking distances, service frequency, and multimodal layers, enabling even more comprehensive assessments of the interplay between spatial configuration and transit provision.

CRediT authorship contribution statement

Tazyeen Alam: Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Miguel Saraiva:** Writing – review & editing, Supervision, Project administration, Data curation, Conceptualization. **Chiara Garau:** Writing – review & editing.

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Data availability

The data that has been used is confidential.

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