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Diagonal equity: bridging horizontal and vertical equity in public transport access



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Equitable public transport (PT) provision requires balancing often competing principles: horizontal equity, serving population demand, and vertical equity, prioritizing social needs. This paper introduces diagonal equity, a novel metric integrating both dimensions into a unified framework. Using the Metropolitan Area of Porto as a case study, walking access to PT stations was evaluated alongside population demand and social needs at the census-block level using principal component analysis of demographic and socioeconomic variables. Horizontal and vertical equity were assessed through accessibility gaps relative to demand and needs, while diagonal equity was evaluated using the potential captive demand, accounting for both. Results show that potential demand is concentrated in central municipalities, whereas social needs are dispersed across suburban and rural areas. Diagonal equity identifies disadvantaged areas where access fails to serve demand-needs, providing a more nuanced view than individual equity assessments and a practical decision-support tool for inclusive PT planning and design.

Efforts in contemporary transport policy development and decision-making increasingly emphasize the need to plan and design public transport (PT) systems that are more accessible, equitable, and demand-sustainable to better serve the needs of disadvantaged groups in society, so that they emerge as a preferred mode of transportation^{1,2}. Demographic shifts, driven primarily by population growth and migration towards urban centers, have pushed low-income groups from city centers to the suburbs (automobile-oriented areas) mainly due to higher living costs resulting from higher demand³. Although policies have aimed to curb private car ownership and travel, mobility gaps persist and are expected to prevail in the future, reinforcing the need for PT and the better integration of buses with rail services that provide faster mobility for both long and short trips. At the same time, a significant proportion of the population in society cannot afford private cars and depends solely on PT to reach urban centers and employment, healthcare, education, and other required destinations^{4,5}. Employment clusters, such as industries and economic zones, are often located outside cities in the peripheries and suburban areas and remain poorly served by PT^{6,7}, forcing people to depend on private transport modes and contributing to “transport poverty,” which restricts equal access to opportunities^{8,9}. Urban expansion has generated a wide range of daily activities necessitating travel, while the suburbanization of disadvantaged populations and transport poverty have intensified barriers to essential services. With only a small percentage of the population having walking access to public transport services (PTS), other active modes of access options, such as cycling, also remain limited due to infrastructural and behavioral limitations^{10,11}. As a result, the provision of PT infrastructure, critical for social and territorial

cohesion¹², continues to contribute to serious spatial and social inequity for those lacking adequate or direct access^{13,14}.

Improving accessibility to PT and connecting people more effectively to jobs and daily activities are essential to empower disadvantaged population groups to become more self-sufficient and improve their quality of life. Achieving these goals necessitates a strategic redesign of existing networks by either extending existing lines or introducing new lines in underserved areas and by addressing structural barriers to access. While these investments aim to reduce disparities among cities and regions, they sometimes exacerbate them^{15,16}. Consequently, the equitable distribution of PTS is a multi-dimensional concept that must be analyzed and systematically incorporated into the transport planning process¹⁷. The existing methods in practice for measuring and incorporating social cohesion goals, however, are limited in their ability to capture the reciprocal relationship between accessibility, population distribution, and social equity^{18,19}. The vulnerability of the population groups dependent on public transit, including the young, elderly, unemployed, and marginalized, mandates a more robust, integrative method to evaluate accessibility distribution and identify inequities. To address this gap, this study introduces diagonal equity, a novel framework that combines accessibility-equity considerations by jointly accounting for potential population demand and social needs. By synthesizing these dimensions, diagonal equity offers a more holistic approach to diagnosing access gaps and guiding equitable PT planning. Providing alternative PT modes in areas with inequities, tailored to their demands and needs, is the primary motivation and aim of this study.

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Guaranteeing people's access to services is the primary and most critical objective in the transportation policy and planning process²⁰. Accessibility is defined as "the potential of opportunities for interaction"²¹, or as a person's ability to reach necessary or desired activities²². In the context of PT, accessibility refers to the ease with which people can access stations, and opportunities can be measured in terms of the services available at those stations, which in turn can influence overall accessibility²³. It serves as a measure to evaluate the efficiency of a PT system in the context of economic, social, and ecological transport scenarios. Accessibility is pivotal to key physical components of urban structure: people, transport, and daily life activity locations Fig. 1²⁴. These components are interrelated, dynamic in nature, and influence one another to create needs and opportunities. Hence, the accessibility landscape changes based on available transport modes, people's accessibility and mobility needs, and their interaction depending on the activity locations and services provided. For population groups reliant on transit, access to the PTS is a primary and crucial component of the accessibility framework, connecting people to activities.

In society, accessibility is argued to be as important as income and wealth since it is a precondition for obtaining them by enabling access to transport and reaching activity centers. Therefore, accessibility is regarded as a social good, similar to income and wealth²⁵. Accessibility analysis encompasses both spatial and socioeconomic aspects²⁶ and is particularly effective at defining and measuring how transport and its development benefits are distributed across geographical areas or population groups, as well as assessing their alignment with cohesion objectives^{16,27}. However, the conclusions drawn from accessibility analyses are sensitive and highly influenced by how PT accessibility distribution is conceptualized and measured²⁸.

The transport literature has discussed the role of equity in transportation, particularly for disadvantaged segments of society and populations experiencing transport poverty^{18,29}. While researchers are of the view that equity is an important consideration when distributing transport benefits, they have provided different conceptions and definitions of equity for evaluation. Theoretical foundations and principles of transport justice draw from the works of Rawls' "A Theory of Justice"³⁰ and Walzer's "Spheres of Justice"³¹. Although Rawls' framework offers a useful foundation for transport justice, Walzer's Sphere of Justice more clearly articulates how benefits should be distributed among the population. Walzer argues that socially meaningful goods such as access, health, and schools require a distinct distributive sphere aligned with their specific social functions³². Transport scholars have adopted different distributive approaches, outlining the underlying principles in practice, summarized in Table 1.

Each framework offers distinct normative guidance for assessing fairness in transport provision. For example, sufficientarianism requires defining an accessibility threshold below which improvements are

prioritized—a step that presents methodological and ethical challenges. Prioritarianism mitigates these by weighing improvements according to individuals' positions along a continuous distribution rather than relying on a strict threshold. Ultimately, equity is a multidimensional concept with diverse applications in research, depending on the context, circumstances, and perspective. It has been defined inconsistently across the literature, often overlapping with notions such as equality, justice, and accessibility. As noted by¹⁹, this conceptual fragmentation has led to divergent interpretations and a lack of coherence in how equity is operationalized in transport planning. With most studies operationalizing it through two widely used lenses^{33,34}.

1) Horizontal equity: rooted in fairness and egalitarian principles, this concept highlights spatial inequalities within a region or society. It emphasizes the need for a fair distribution of resources and equitable access to services³⁵.

2) Vertical equity: based on Rawlsian theory, addresses inequalities among individuals and different groups with varying needs, including (a) income and social class-related disadvantage and (b) mobility needs and ability-related disadvantage^{36,37}. These dimensions provide the conceptual basis for evaluating how PTS are distributed across different areas and population groups with distinct socioeconomic characteristics.

Transportation planners and policymakers have gradually adopted an equity lens in assessing and developing transportation systems that promote social inclusion and address the needs of disadvantaged groups, recognizing its potential to improve people's living standards³⁸. Accessibility serves as a key indicator of PTS distribution, reflecting how well PT serves disadvantaged populations. Prior studies have applied accessibility analysis to various contexts, including equity distribution issues, employing equity mapping³⁹, healthcare delivery⁴⁰, urban service delivery^{41–43}, and issues of transit accessibility and social disparity^{44,45}.

Horizontal and vertical equity assessments typically rely on socioeconomic and demographic information such as population, density, age, income, employment, rents, disability, and car ownership^{44,46–49}. Additionally, other vulnerable population groups, such as students, children, and workers by job type, have also been considered to define zonal spatial equity measures⁵⁰. Vertical equity is commonly examined through socioeconomic disadvantage (income and social class) and mobility-related needs, including disabilities and car availability, where zero or forced car ownership is a major contributor to transport disadvantage^{51,52}. Depending on the data available, studies have relied on different variables from these groups^{29,38,42,49,53–56}.

Moreover, A range of metrics has been applied to quantify equity outcomes. Horizontal equity is often measured using distributional indicators such as the GINI coefficient^{36,57}, the Theil indices⁵⁸, and the Atkinson¹⁵. As horizontal equity fails to address inequalities among disadvantaged groups⁵⁹, vertical equity provides a complementary approach and is evaluated using measures such as the transport needs index^{60,61}, social indicator, and social vulnerability indicator^{44,49}, transit needs index⁶², and participation index⁶³. While these measures reveal important disparities, they typically evaluate demand (horizontal equity) and social needs (vertical equity) as separate constructs, offering limited guidance for integrated decision-making. This fragmentation is increasingly problematic, as equitable transport planning requires understanding not only where demand exists but also where social vulnerabilities intensify the consequences of limited access. This fails to capture the complex and interdependent nature of inequities produced by transport systems, limiting their usefulness for integrated planning decisions¹⁹.

While accessibility and equity have been extensively measured, few frameworks explicitly integrate demand and social need simultaneously in an operational way for a unified assessment. Thus, the contribution of this study lies in addressing this gap by developing a methodological approach, outlined in the subsequent section, that quantifies potential demand, social needs, and proposed potential captive demand as the basis for a holistic equity assessment. Building on egalitarianism and prioritarianism, we introduce a third lens, diagonal equity, which integrates both horizontal and vertical equity dimensions, providing a clearer understanding of where PTS

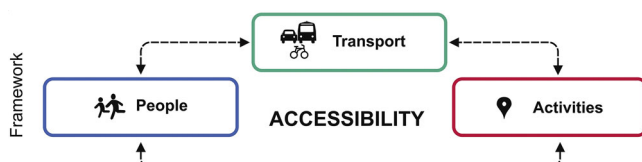


Fig. 1 | Accessibility landscape. The figure illustrates the conceptual accessibility framework adapted from research study²⁴. Accessibility is represented as the outcome of interactions between people, transport systems, and activity opportunities. The people component represents individuals and households, the transport component represents available travel modes, including public transport and active modes, and the activities component represents destinations such as employment, education, and services. Dashed arrows indicate feedback mechanisms through which accessibility influences travel behavior, transport provision, and activity location patterns.

Table 1 | Summary of key theories of justice relevant to transport equity

Theories of Justice	Core Principle	Implication for Transport Equity	Contributing studies
Egalitarianism	Equal benefits for all.	Advocates for uniform access to transport services.	33,68
Rawlsian Justice	Prioritize the least advantaged.	Directs resources to groups with the lowest accessibility.	30,32
Walzer's Spheres	Different goods require distinct distributive rules.	Frames accessibility as a social good needing its own justice criterion.	31,32
Utilitarianism	Maximize total welfare.	Maximizing the overall benefit of society.	86
Sufficientarianism	Everyone should have "enough."	Establishes minimum accessibility thresholds to be met.	18,60
Prioritarianism	More weight to worse-off groups.	Prioritized benefits for individuals based on location on the distribution spectrum/degree of disadvantage.	87

should be prioritized to balance demand pressures with social need, and enabling more targeted and equitable interventions.

Methods

The proposed equity assessment is based on the levels of accessibility available to PTS and the demand and needs derived from the demographic data for a geographic area. We begin by calculating the accessibility levels using spatial analysis techniques, and the process is subdivided into two sections: 1) travel time calculation: for the given urban and suburban transport infrastructure, travel times from the census blocks (the smallest geographic level) to the nearest rail and bus stations were calculated for walking. A network dataset was modeled in ArcGIS software to determine the walking distances and times. 2) Determining accessibility levels: gravity measures were used to calculate the accessibility levels using the cost of travel given by travel times, a decay coefficient, and incorporating the attractiveness at each station, measured by the frequency of services at rail and bus stations.

The method of horizontal, vertical, and diagonal equities assessment is subdivided into three sections:

1) demographic information: We begin by selecting suitable demographic variables based on the population, social, economic, and household information to establish a measure of demand and needs. To assess the dimensions of horizontal equity, variables related to population groups were used, and, for vertical equity, socioeconomic variables were used that best define the demand and needs for PTS in the area. Based on these criteria and available data, a total of twelve variables were chosen.

2) measures of potential demand and social needs: We employed principal component analysis (PCA) to quantify the potential demand and needs based on the selected variables. Two principal components were identified that best describe the potential demand and social needs for PT.

3) equity analysis: Using the results from the PCA, two components describing the relative demand and needs across the areas were combined to formulate a final measure of potential captive demand. The quantified measures for potential demand and needs allowed us to calculate the horizontal and vertical equities, respectively. Based on the potential captive demand, we calculated diagonal equity to identify areas requiring higher levels of accessibility, considering both needs and demand. The difference between access to PTS and the potential captive demand gave a reference value for diagonal equity.

Accessibility calculation

The primary measure of access is the proximity or physical separation between the origins and destinations, typically measured in terms of minimum distance or time. Several factors influence this measurement, including the spatial distribution of origins and destinations, the efficiency of transport systems, and the attractiveness of the destinations. People choose different modes to access the PTS, such as active modes like walking and cycling, and passive modes like private cars, depending on the availability and utility. In this study, we considered walking, the most common active mode, to calculate access to the nearest rail and bus stations (destinations) from each census-block's centroid (origin). The basic mathematical

formulation for calculating access to stations using time is given by Eq. 1.

$$A_{mi} = \min t_{mij} \quad (1)$$

where:

A_{mi} is the access at census-block i to its nearest station j by mode m (walking), and t_{mij} are the travel times between origin i and the nearest station j by mode m (walking) for the different available routes (in minutes).

Various place-based measures have been used to measure access, including minimum distance, gravity measures, and cumulative opportunities^{64,65}. While minimum distance calculations focus on the shortest path to stations, cumulative measures also incorporate a minimum threshold distance or time to include all accessible opportunities. Gravity-based accessibility measures, on the other hand, enable the incorporation of the cost of travel time between origins and destinations through a decay function, as well as the attractiveness of the destinations⁴³. In this context, the modified gravity measure uses a decay function that expresses the cost of physical separation between the origin (census block) and the destination (nearest station), accounting for the attractiveness as the level of service at the destination. This approach is formulated in Eq. 2.

$$A_{mi}^* = a_j \cdot \exp[-\lambda_m \cdot \min(t_{mij})] \quad (2)$$

where:

A_{mi}^* is the access at census-block i to its nearest station j by mode m (walking), considering distance decay and the station's attractiveness,

λ_m is the impedance coefficient of mode m (walking),

a_j is the attractiveness at station j , measured by the average number of trains/buses per week, such as $a_j = \frac{\text{number of trains/buses at } j}{\text{maximum number of trains/buses in the network}}$.

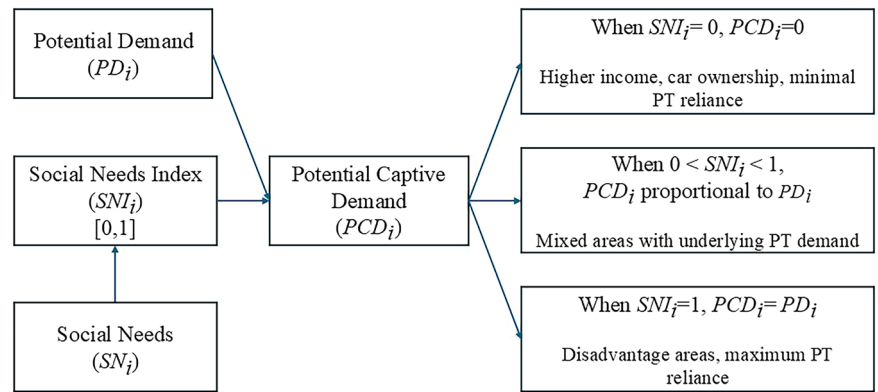
The impedance coefficient is usually derived from origin-destination (OD) trip data collected in travel surveys. Due to the unavailability of trip data for PT stations, we derived the value for λ_m , i.e., 0.08, based on preferred walk times and distances to rail and bus stations from the geographic locations where people live. We used an average walking speed of 5 km/h to calculate walking times, based on a maximum 15-min walk. This approach aligns with the 15-min city concept, which aims to ensure that all essential services are reachable within 15-min⁶⁶. People living closer to the station have better access, and this access diminishes with increasing time, becoming negligible beyond the 15-minute walk.

Demand and needs measures using principal component analysis (PCA)

Various methods have been employed to identify significantly correlated variables and calculate weights among demographic groups, including regression analysis^{62,67}, factor analysis⁶³, and aggregation methods like multi-criteria analysis MCA and analytic hierarchy process AHP^{68,69}. In this study, we used PCA, a multivariate numerical analysis tool that reduces the dimensionality of large datasets by transforming them into a smaller set of uncorrelated variables called principal components. These components are linear combinations of the original variables. PCA is particularly useful for

Fig. 2 | Conceptual schematic of the PCD measure.

The figure illustrates the derivation of potential captive demand from potential demand and social needs. Potential demand represents the demographic demand for public transport, while social needs are transformed into a standardized Social Needs Index (SNI) ranging from 0 to 1. Three illustrative cases are shown: an SNI value of 0 results in no captive demand, intermediate values proportionally scale captive demand, and an SNI value of 1 yields captive demand equal to potential demand, representing highly disadvantaged and transit-dependent populations.



deriving the weightage of demographic variables to quantify an aggregated index^{60,70–73}. PCA helps in estimating composite measures by capturing the maximum variance in the original variables and assigning the largest weights to those with the largest variation within the dataset.

Before quantifying the principal components, a normalization of the original variables is required; thus, the x 's correlated variables will be transformed into the z -scores. The normalization process standardizes the demographic variables in use with Eq. 3.

$$z = \frac{x - \mu}{\sigma} \quad (3)$$

where x is the value for the demographic variable, while μ and σ are the mean and standard deviation for the demographic variable.

Using the extracted principal components, an aggregated value is calculated by multiplying the normalized value of each variable by its associated weight in the PC and summing the products, as defined in Eq. 4.

$$PC_i = \sum_{k=1}^n w_{ki} z_k \quad (4)$$

where, w_{ki} is the correlation weight, and z_k is the normalized value of the k^{th} variable x for every PC i .

Based on the results of PCA obtained from the demographic and socioeconomic datasets, we can identify which components represent potential demand and which represent needs. For each census-block, the potential demand measure from PC_1 is mainly influenced by demographic characteristics, and the social needs measure represented by PC_2 , is based on socioeconomic variables such as income, car usage, and household characteristics. To ensure that these assignments were methodologically robust rather than dependent on a particular PCA configuration, we tested alternative rotations and examined clustering patterns in the component scores. These procedures consistently produced the same grouping of variables, supporting the reliability of interpreting PC_1 as demand and PC_2 as needs.

To enable a holistic analysis of equity, capturing both potential demand and social need in a single metric, we defined potential captive demand (PCD_i) as the product of potential demand measure (PD_i) and a social need index (SNI_i) computed using Eq. 5 for each subsection i . It provides a more need-centric measure of demand, as depicted in the schematic diagram in Fig. 2. The social need measure (SN_i) was transformed to SNI_i , ranging from zero to one, using Eq. 6.

$$PCD_i = PD_i * SNI_i \quad (5)$$

$$SNI_i = \frac{PC2_{max} - PC2_i}{PC2_{max} - PC2_{min}} \quad (6)$$

When the SNI equals “0”, the potential captive demand is also 0, reflecting areas characterized by high incomes, car ownership, and a strong preference to use private cars, where reliance on PT is minimal. Conversely, for maximum needs, the SNI equals “1”; the potential captive demand matches the potential demand, indicating areas with the greatest socioeconomic disadvantage and the highest likelihood of PT dependence due to fewer mobility options. For intermediate SNI values between 0 and 1, the potential captive demand scales proportionally with potential demand. This formulation provides a concise way to identify locations where limited mobility options amplify the underlying demand for PT, offering a practical basis for prioritizing investment.

Equity measures

A linear combination of the assigned weights derived from the principal components and the corresponding demographic variable yields measures of potential demand, needs, and potential captive demand, which are then used to assess inequities. A gap-based approach was adopted to analyze the inequity between the available level of access to PT stations and the measures of demand and needs for these services^{54,56,62,71}. The potential demand measure, which includes the total population and demographic characteristics, allows us to calculate horizontal equity (HE_i) for each subsection i . This is determined by the difference between access and potential demand, as described in Eq. 7, and ensures that all the populations have equal access to PTS, regardless of need. In contrast, the need measure accounts for the area's needs based on its socioeconomic characteristics, and the difference between access and needs provides a measure of vertical equity (VE_i) for each subsection i , given by Eq. 8. To ensure comparability across the measures of walk access, PD_i , SN_i , and PCD_i with different ranges, the measures were normalized using z -scores (Eq. 3).

$$HE_i = zA_{mi}^* - PD_i \quad (7)$$

$$VE_i = zA_{mi}^* - SN_i \quad (8)$$

While horizontal equity focuses on equal distribution across the population and vertical equity prioritizes addressing needs, it is challenging to achieve both simultaneously. Providing services to everyone to meet horizontal equity would require significant investment from public funds, potentially neglecting the needs of disadvantaged groups. On the other hand, achieving vertical equity requires reaching areas with the most needs, necessitating fixed, flexible, and on-demand services that may not be demand-efficient or cost-effective. Thus, a balance between horizontal and vertical equity is essential, based on the potential captive demand. The difference between access and potential captive demand provides a measure of diagonal equity (DE_i), given by Eq. 9.

$$DE_i = zA_{mi}^* - zPCD_i \quad (9)$$

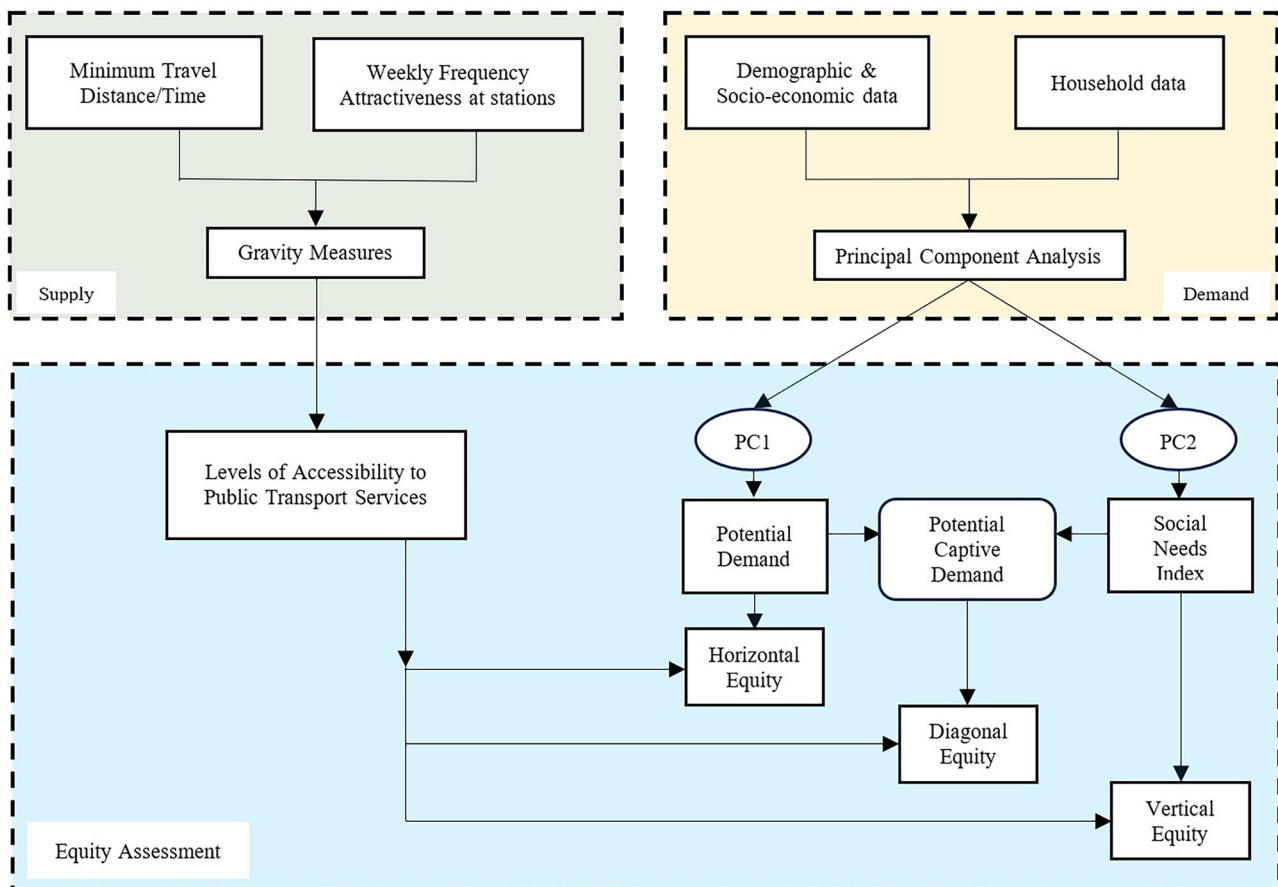


Fig. 3 | Framework for assessment of equity dimensions in PTS distribution. The figure presents the overall methodological workflow linking supply and demand components and the equity assessment. Supply and demand components are

integrated to evaluate three dimensions of equity: horizontal, vertical, and diagonal. Arrows indicate the sequence of data processing and information flow between framework components.

where z represents normalized values of access and potential captive demand for subsection i .

The proposed methodology consists of three key components: accessibility analysis of PTS (supply), demand and needs assessment based on demographic and socioeconomic parameters, and evaluation of the different dimensions of equity as outlined previously. Figure 3 illustrates the equity assessment framework.

Study area

The case study in this work focuses on the Metropolitan Area of Porto (AMP), comprising 17 municipalities with approximately 1.75 million inhabitants as of the 2011 census. The AMP is served by a transit system that includes metro and suburban trains, providing connectivity between the central municipality of Porto and its surrounding suburbs and other municipalities. Figure 4 shows the geographical representation of the PT network components, including the metro, rail, and bus stations, serving the municipalities of AMP.

The metro network is more concentrated in the northern municipalities, with the highest services in Porto. It also extends to serve the municipalities of Maia, Vila do Conde, and Póvoa de Varzim to the north, Matosinhos to the west, and some parts of Gondomar (east) and Vila Nova da Gaia (south). The main broad-gauge train lines pass through Porto, Gondomar, Maia, Trofa, Santo Tirso, Valongo, and Paredes to the north and north-east and through Vila Nova da Gaia and Espinho to the south. A narrow-gauge line starts in Espinho and serves the southern municipalities of Santa Maria da Feira, São João da Madeira, and Oliveira de Azémeis. Notably, the municipalities of Arouca and Vale de Cambra are not served by any rail service. The service frequency is significantly higher at metro

stations, with a maximum of 1258 trains and a minimum of 130 trains per day. The broad-gauge lines have a frequency ranging from a maximum of 481 to a minimum of 33 trains passing each day. In contrast, narrow-gauge train services have a relatively low daily frequency, with a maximum of 16 trains and a minimum of 4 trains. The bus system is operated by two major agencies, STCP and UNIR. STCP primarily operates within the Grand Porto area, encompassing the central municipality of Porto and its neighboring municipalities. Meanwhile, UNIR operates across all 17 municipalities of AMP, offering urban, interurban, and suburban services. PT stops for both rail and bus are distributed sparsely in the outer municipalities and densely concentrated in the central municipalities.

With the assumption that poverty has grown outside the central business district (CBD) and that socially disadvantaged groups are spatially concentrated and more dispersed throughout the metropolitan areas⁷⁴. We selected the lowest spatial scale available for our analysis because the data variables were already aggregated to this geographical level. The lowest level of Portuguese census blocks is referred to as a subsection, as defined by INE, comprising a total of 22,699. Each subsection corresponds to a territorial unit, whether built-up or not, within a statistical section, representing a block in urban areas, a locality or part of a locality in rural areas, or residual areas which may or may not have dwellings. The parent category is the statistical section, corresponding to a territorial unit with approximately 300 dwellings. Although selecting census tracts for analysis units can induce some partialities using the centroid's locations in accessibility measurement for the large census blocks, these partialities were minimal for relatively smaller census tracts and with a dense walking network⁷⁵. Evidence indicates that using a micro spatial scale results in marginal differences in the final results^{76,77}.

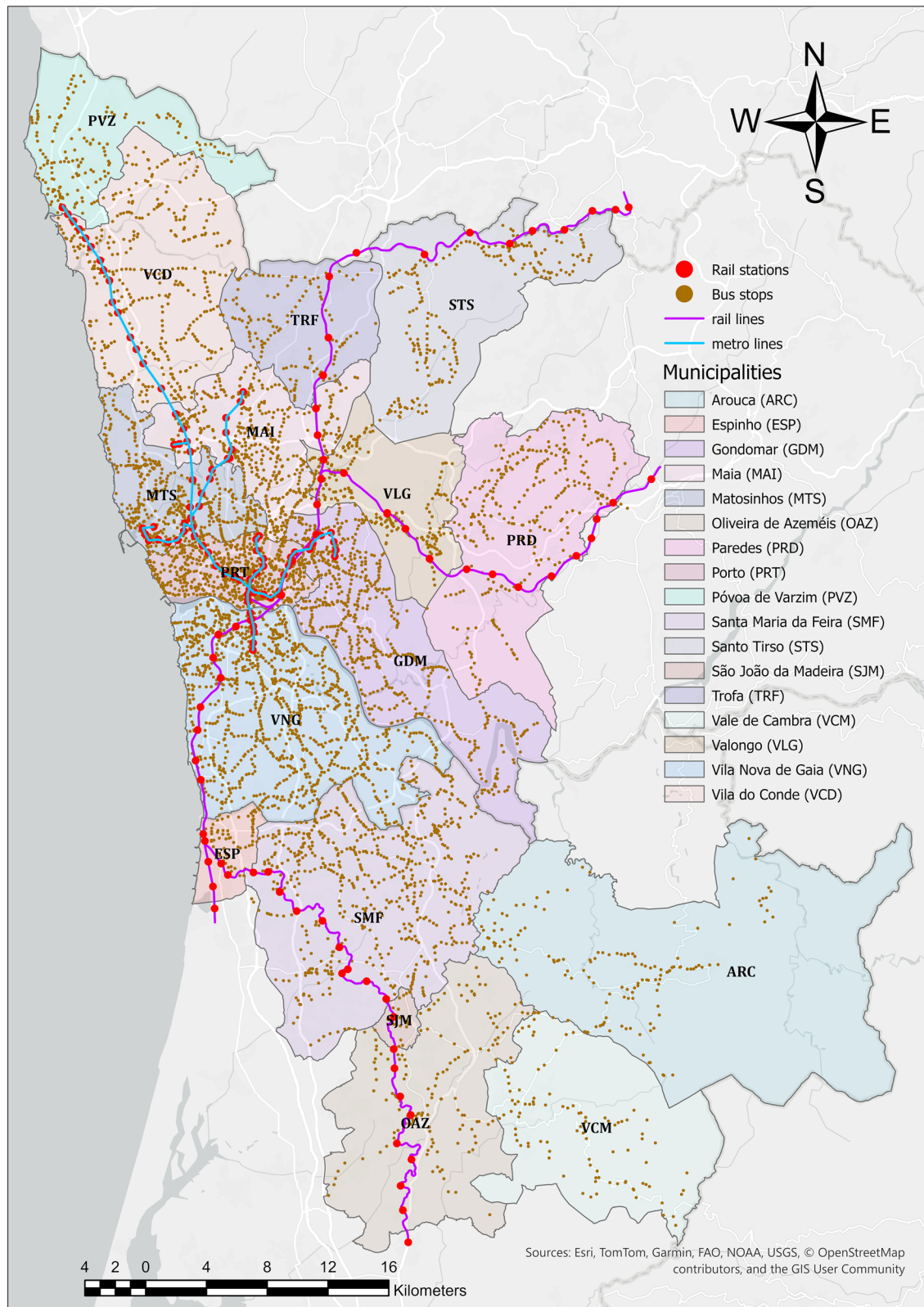


Fig. 4 | Study area of the Metropolitan Area of Porto. The figure shows the study area and the public transport network within the Metropolitan Area of Porto (AMP). Municipal boundaries are displayed as colored polygons and labelled with

municipality names and acronyms. Rail stations are represented by red circles, bus stops by brown circles, rail lines by purple lines, and metro lines by pink lines. A north arrow and scale bar provide geographic reference.

Demographics data for AMP was obtained from the 2011 census conducted by⁷⁸, because the 2021 census data was not available at the subsection level at the time of this analysis. We selected the variables of population, household characteristics, car ownership, income, and

land value. The demographic variables include the total resident population, total female population, total student population, total dependent population (less than 15 years and higher than 65 years), total unemployed population, and the social class variable, including

the population receiving welfare benefits and monthly pensions dependent on social benefits. Second, for household characteristics, we considered the number of houses smaller than 50 m², larger than 200 m² and the number of houses with parking for two or more cars. Given the varying geographic sizes of the subsections, rather than using the absolute values of the demographic variables, we calculated density, i.e., the total number per km². This approach better reflects the population distribution in the region and is helpful in estimating the demand and needs across different areas. Population density is widely used by different studies in accessibility, equity, and urban research^{46,79,80}. Data on the average percentage of trips made by car and households with available parking spaces were used as proxies for car ownership. Third, we considered the average declared income per inhabitant for each census block. Finally, we have the value of rent per household, which relates to land prices in the area. These variables collectively define the socioeconomic characteristics of the area. A summary of selected data variables for AMP by municipality is shown in Table 2.

Results

In this section, we present our analysis and the results obtained. First, we discuss walking access to the rail and bus stations, and the distribution of maximum access across the AMP. Next, we detail the results of the PCA of demographic and socioeconomic characteristics, explaining how we calculated the potential demand, needs, and potential captive demand for each area. Finally, we assess the horizontal, vertical, and diagonal inequities in access to PTS throughout the AMP and discuss potential improvements through the integration of alternative transportation modes.

Walking accessibility

The spatial analysis for this part was conducted using ArcGIS, a geographic analysis software. We utilized census-block shapefiles and datasets from INE, with unique reference codes for the subsection's spatial level. Some of the data related to PT stop locations and lines was available from the official organization websites, and the rest of the data, including the road network, was extracted from the BBBike⁸¹ and refined for this paper. The network dataset was built for walking mode, and the walking distance and time from each subsection's centroid (snapped to the nearest road segment) to the nearest rail and bus station were calculated using the Closest Facility Location Tool in Network Analyst. Using walking time from census blocks to the nearest rail and bus stations, the impedance coefficient, and stations' attractiveness in terms of service frequency, we calculated access levels for each census block using the gravity measure. These access levels were then mapped across AMP. The distribution of the maximum walking accessibility index to PTS is depicted in Fig. 5, with a sequential color scale (light to dark) to intuitively represent the cumulative nature of accessibility, from yellow (indicating the lowest access) to purple (indicating the highest level of access).

Predictably, better access is concentrated along metro and rail lines and in proximity to stations. Porto municipality exhibits the highest access levels, benefiting from its central location and better share in the distribution of stations and higher frequencies of metro, rail and bus. In general, greater access levels are observed along metro lines, which tend to have higher attractiveness/service frequency at stations than rail lines. Conversely, the narrow-gauge train line and sparsely located bus stops serving the southern municipalities provide lower access levels resulting from their lowest attractiveness. Walking access to PTS is especially favorable in central areas of Porto and Matosinhos, as well as in the northern parts of Vila Nova de Gaia, constituting the urban areas with the highest number of stations, particularly metro stations, compared to the other parts of AMP. Municipalities served exclusively by metro lines, such as Matosinhos, Maia, and Vila do Conde, demonstrate better walking access compared to those served only by trains, like Valongo, Paredes, and Santo Tirso, as the stations are located closer to each other.

Potential demand and needs measures

The following results were obtained from the PCA, conducted using SPSS to extract components and analyze correlations among the independent demographic variables. Table 3 presents a Kaiser-Meyer-Olkin (KMO) value of 0.870, indicating the adequacy of the data for the analysis.

The PCA revealed two significant components, PC1 and PC2, based on eigenvalues > 2, which collectively account for approximately 70% of the total variance. From the component matrix (Table 4), the two components, PC 1 and PC 2, were selected for our analysis to represent potential demand and needs measures, respectively.

Potential Demand: PC 1 shows a strong positive correlation with demographic population groups and is weakly associated with large dwellings and car usage, indicating that it captures density-driven potential demand for PT, particularly in more populated regions.

Needs: PC 2 reflects socioeconomic and mobility-related disadvantages as it has the highest positive correlation with car usage, followed by rents, income, and larger households with parking, and a negative correlation with lower-income and socially vulnerable groups. These patterns collectively indicate that lower car ownership, lower income, and smaller dwellings correspond to greater reliance on PT. Thus, PC2 provides an effective measure of socioeconomic needs and reliance on PT.

The resulting measures characterize each census block, ranging from negative to positive, using Eq. 4. PC1, with maximum weights on population variables, represents potential demand, with negative values depicting lower demand and positive values depicting higher demand. PC2 provides information about the needs. Negative values resulting from lower car usage, low income, and lower land value indicate higher needs, while a positive value for PC2 implies lower needs.

The spatial distribution of potential demand across the AMP is shown in Fig. 6. A graduated color scale (light to dark) is employed to effectively represent the wide range of values, clearly differentiating zones of low, moderate, and high potential demand. Darker areas identify census blocks with high potential demand, predominantly in Porto, urban centers, and the fringes of municipalities, as well as in suburban areas. Light-colored areas indicate census blocks with low or zero population, often comprising unbuilt or green free spaces. These blocks surrounding urban centers feature various land uses, including industrial zones, hospitals, schools, shopping centers, parks, recreational areas, and ports. While they do not generate residential population demand, they require PT access to serve the needs of employees and people who visit these areas for daily life activities.

Figure 7 illustrates the needs distribution using a diverging color scale to highlight geographic clustering, whereas a sequential scale was used for potential demand to represent intensity. This distinction visually emphasizes where needs are concentrated—a key focus in equity analysis—rather than only their magnitude. Areas with maximum needs, colored red to yellow, are primarily located away from stations and urban centers, in the urban fringes and suburban areas. High-needs census blocks are located in Vila do Conde in the north, in Paredes, Gondomar to the east, in the eastern parts of Vila Nova de Gaia, and in parts of Espinho, Santa Maria da Feira, Arouca, and Vale da Cambra in the south. The needs distribution shows that most areas around rail lines or in areas with better PTS have higher needs, which can be associated with lower car ownership since the people living in these areas have better access to PT stations by walking, as shown in Fig. 4. This pattern is more dominant for the metro and buses, as they serve densely populated regions, offer better frequency and have stations located closer to each other than rail lines. The municipality of Espinho is characterized by high needs due to a higher concentration of rail stations, which provide better access to residents and result in lower car usage. In contrast, areas in the north of Espinho, constituting parts of Vila Nova de Gaia, and south of Espinho, including municipalities of Santa Maria da Feira, São João da Madeira, and Oliveira da Azemeis, exhibit low needs for PT. These areas are served by lower levels of PTS, which force people to own cars, leading to a higher percentage of trips made by car (72.38%, 72.66%, and 66.67%, respectively). Additionally, the municipality of Vale de Cambra, which lacks

Table 2 | Demographic and socioeconomic data summary of AMP municipalities

Municipality	Area (km ²)	Females/km ²	Population/km ²	Dependent/km ²	Students/km ²	Social class/km ²	Unemployed/km ²	House parking 2+ /km ²	House size < 50m ² /km ²	House size > 200m ² /km ²	Car usage %	Rent value (monthly)	Income per person
Arouca (ARC)	329.1	35.13	67.94	22.75	12.69	41.29	1.92	8.65	1.89	2.39	63.92	185.38	5707
Espinho (ESP)	21.1	790.24	1506.45	502.23	253.98	985.59	104.60	111.90	56.07	36.87	55.92	173.24	8245
Santa Maria da Feira (SMF)	215.9	333.07	645.26	197.61	128.80	332.88	40.66	82.02	15.50	24.03	72.38	195.11	6549
Oliveira de Azeméis (OAZ)	161.1	219.30	425.89	134.83	78.93	238.44	15.41	56.65	10.72	17.13	72.66	199.36	7359
São João da Madeira (SJM)	7.9	1454.56	2748.48	848.23	517.09	1475.82	132.53	162.15	58.10	71.65	66.67	196.27	8290
Vale de Cambra (VCM)	147.3	80.01	155.22	52.46	26.84	101.56	4.60	20.58	4.13	5.82	74.88	203.80	7544
Gondomar (GDM)	131.9	659.74	1273.90	386.77	263.37	686.22	89.27	95.14	50.15	28.54	59.73	168.38	7004
Maia (MAI)	83	848.81	1630.19	492.58	325.08	780.20	100.41	160.14	46.08	48.39	69.86	234.85	8762
Matosinhos (MTS)	62.4	1474.90	2812.15	855.72	535.16	1564.52	174.98	185.79	117.77	60.98	61.15	229.73	9124
Paredes (PRD)	156.8	282.68	553.92	165.28	114.16	251.68	35.18	206.53	19.49	15.73	58.88	189.48	5091
Porto (PRT)	41.4	3127.71	5738.91	2015.99	1052.95	3997.42	367.49	312.44	406.55	156.18	51.42	191.49	12131
Póvoa de Varzim (PVZ)	82.2	406.93	771.39	242.20	153.86	405.21	43.72	64.60	13.93	26.68	60.10	242.49	6798
Santo Tirso (STS)	136.6	272.30	523.65	162.62	94.48	312.70	39.80	64.28	15.18	18.42	64.72	184.47	6751
Valongo (VLG)	75.1	650.36	1249.77	373.17	261.50	621.96	89.79	89.16	38.75	27.54	60.72	211.90	6921
Vila do Conde (VCD)	149	275.60	533.78	165.29	102.19	277.42	32.96	50.74	10.99	17.01	62.18	230.81	7208
Vila Nova de Gaia (VNG)	168.5	936.53	1794.04	553.70	346.25	950.79	136.52	151.73	72.85	45.18	62.64	200.25	7869
Trofa (TRF)	72	280.36	541.65	156.82	106.57	267.57	41.22	64.86	11.58	21.83	66.69	244.65	6748

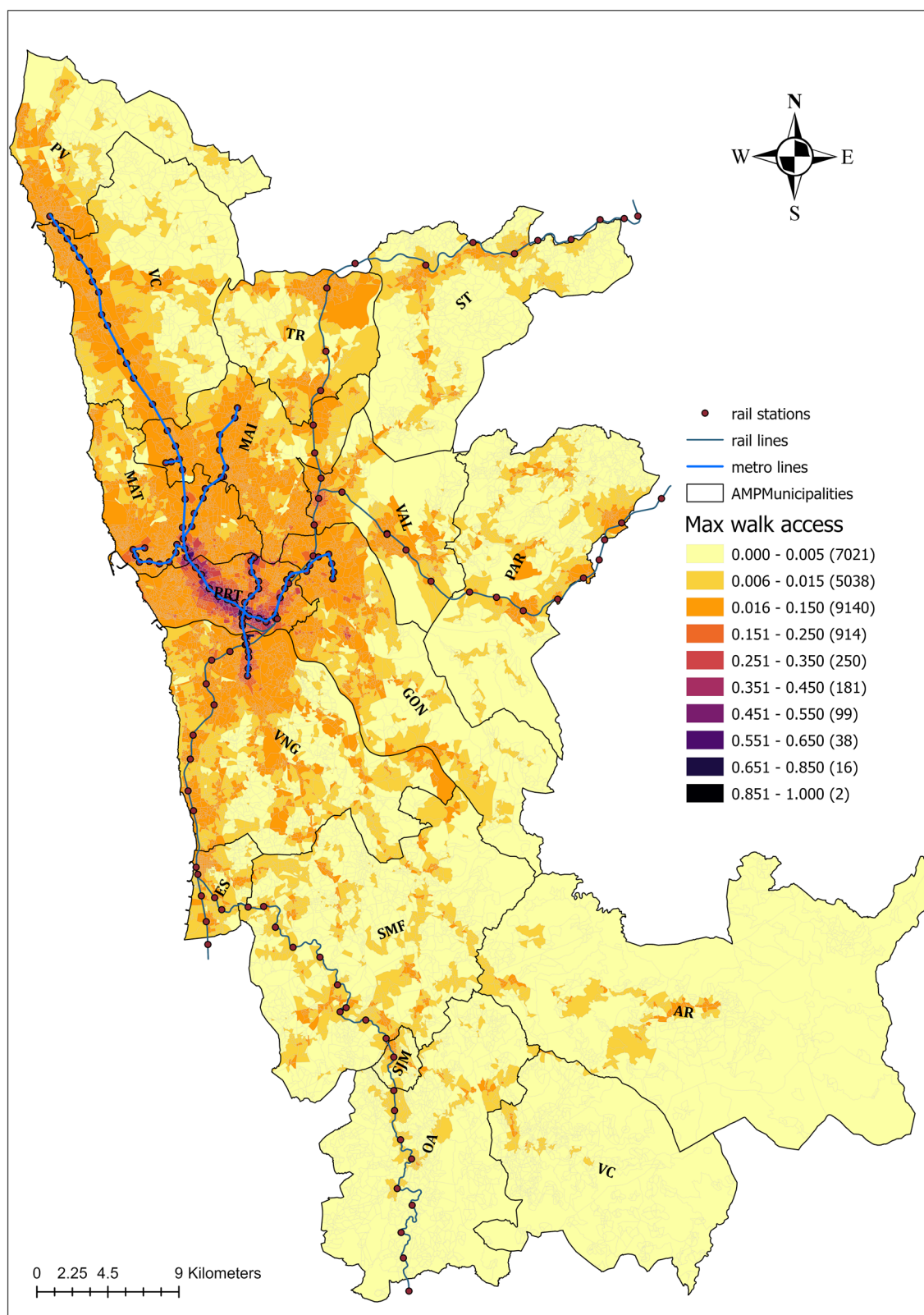


Fig. 5 | Maximum walking accessibility index to PTS. The figure shows subsection-level maximum walking accessibility to public transport services (PTS) across AMP. Accessibility incorporates both walking proximity and service frequency available at the nearest station or stop. Light yellow areas indicate low accessibility, whereas

progressively darker orange and purple areas indicate higher accessibility levels. Rail stations are represented by dark purple circles, rail lines by blue lines, metro lines by light-blue lines, and municipal boundaries by black outlines.

Table 3 | KMO and Bartlett's test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.870
Bartlett's Test of Sphericity	Approx. Chi-Square	354,183.596
	df	66
	Sig.	0.000

Table 4 | Components matrix

Variables	Principal Components	
	PC 1	PC 2
Females/km ²	0.978	-0.090
Pop/km ²	0.977	-0.085
Dependent/km ²	0.961	-0.099
Social class/km ²	0.903	-0.143
Students/km ²	0.893	-0.034
Unemployed/km ²	0.865	-0.182
House size < 50 m ² /km ²	0.617	-0.251
Car usage	0.007	0.849
Rent value (monthly)	0.244	0.816
Income per Individual	0.478	0.606
Houses with parking space 2+ / km ²	0.436	0.316
House size > 200 m ² / km ²	0.289	0.368

access to rail or bus service entirely, has the highest percentage of car trips at 74.88%.

Based on measures of potential demand and needs for the PTS, the potential captive demand distribution was mapped and is illustrated in Fig. 8. A graduated color gradient similar to that of potential demand accurately reveals potential captive demand hotspots and their relative strength proportional to the potential demand corresponding to social needs. With the assumption that higher car usage equals lower PT need can overlook forced car ownership among low-income households in peripheral municipalities with limited services and misclassify areas as low-need. Even in an area where a low-income household is forced to own a car due to limited alternatives, PCD captures the broader potential demand arising from all population groups in that area, alongside their social needs. This means that even if a household has forced car ownership, there may still be other residents, such as the elderly, youth, or non-car owners, who rely on PT. Therefore, such areas are not automatically misclassified as low-need, but with existing captive demand under the proposed framework. The potential captive demand, initially concentrated in urban centers, shows a slight decrease compared to the earlier measure of potential demand, primarily due to lower needs in these areas. However, the zones with the maximum demand, after adjusting for needs, remain centered in the urban center, predominantly within the Porto municipality. A few high-demand areas are also scattered throughout the adjacent municipalities of Matosinhos, Maia, Gondomar, Vila Nova da Gaia, and northward into Póvoa de Varzim. Suburban zones, which generally have poor socioeconomic characteristics, also contribute to the demand for PT. Although the orange-colored zones in Fig. 8 generate less demand than the darker zones in Fig. 6, they have increased in number and spread further into the suburbs, reflecting higher demand driven by greater needs. The light-colored blocks represent areas with no population and, consequently, no demand for PT.

Equity assessment

This paper further evaluates inequities in walking access to PTS, using the horizontal, vertical, and diagonal equity dimensions. Inequities are quantified as the difference between walking access to the nearest station and the corresponding measures of potential demand, needs, and potential captive demand. To ensure comparability across variables with different units and ranges, the walk access, PD_i , SN_i , and PCD_i measures were normalized using z-scores prior to conducting the gap analyses. The resulting horizontal, vertical, and diagonal equity values represent standardized differences between access and each corresponding indicator, where negative values denote higher inequities (i.e., underserved, access insufficient to meet demand or need) and positive values indicate lower inequities (i.e., well-served, access adequately meeting or exceeding demand or need). A diverging red–yellow–blue color scale is applied consistently across all equity maps because it effectively distinguishes negative from positive standardized values. Red denotes higher inequity and identifies underserved areas, blue indicates lower inequity where access is sufficient, and yellow marks values near the equity midpoint. This intuitive and widely used scheme enhances visual comparability across maps while preserving consistent interpretive meaning despite differences in underlying variable ranges.

Horizontal equity justifies the egalitarian principle and reflects whether PTS aligns with population driven potential demand. Figure 9 illustrates the results for horizontal equity. The lowest inequity values (blue) concentrate in the central municipality of Porto, where dense population patterns coincide with extensive metro and bus services. Conversely, areas shown in red and yellow highlight areas where high potential demand is served by lower levels of access to PTS, especially in urban peripheries and the outskirts of adjacent municipalities. Overall, the map indicates limited horizontal inequities, depicted by the predominance of light blue color, largely because many peripheral areas exhibit lower demand and no or limited access. The most disadvantaged zones, where inequities are more pronounced, shown in the red to yellow color range, tend to lie beyond the walkable station catchments, suggesting that targeted bus feeders integrated with the rail system could substantially reduce the demand-access mismatch.

Vertical equity assessment is crucial to determine whether the current PT structure adequately serves disadvantaged groups. Figure 10 uses the same red–yellow–blue color spectrum as in the horizontal equity analysis to illustrate vertical equity but reveals a substantially different spatial distribution pattern. Central areas of Porto and northern Vila Nova da Gaia show low inequities, owing to dense populations with smaller houses, higher incomes, and good service coverage around rail and metro stations. Areas with lower inequity or well-served census blocks are situated closer to rail stations and lines, benefiting from transit-oriented development (TOD) that provides better access, higher incomes, and higher land values. These areas stretch from Póvoa de Varzim in the north to Espinho in the south. However, large portions of the eastern and peripheral municipalities exhibit high inequity values, indicating that socially disadvantaged populations—characterized by lower incomes, smaller dwellings, and lower car ownership—are underserved by the current PTS. More than half of all census blocks fall within ranges indicating vertical inequity. While some of these areas, shown in orange, are not residential but include industrial zones, commercial centers, hospitals, parks, etc., these areas still require adequate PT provision to support employment and access to these essential activities. The pattern underscores persistent socio-spatial mismatches between where services are provided and where they are most needed, which can guide the provision of sufficient services tailored to meet the needs of different areas, justifying the principles of sufficientarianism distribution.

For the same accessibility distribution, the diagonal equity assessment based on the potential captive demand measure integrates both potential demand and needs, placing greater weight on areas where both are high.

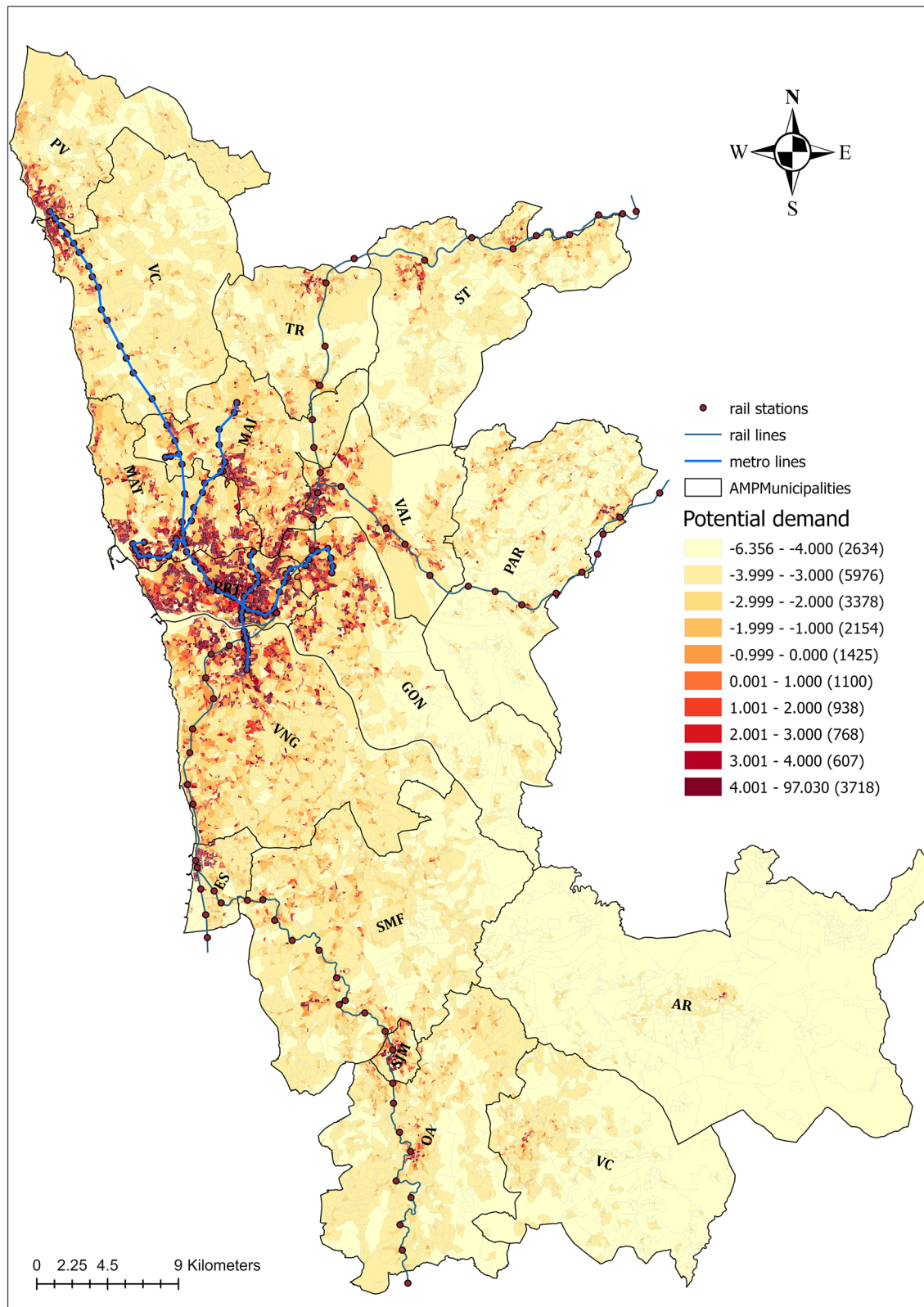


Fig. 6 | Potential demand distribution. The figure presents subsection-level potential demand for public transport derived from demographic characteristics across the Metropolitan Area of Porto (AMP). Light beige areas indicate low

demand, while progressively darker orange and red areas indicate higher concentrations of potential demand. Rail stations, rail lines, metro lines, and municipal boundaries are shown for geographic reference.

Figure 11, depicting diagonal equity, helps to identify these areas using the same color scale.

The diagonal equity pattern resembles that of potential demand, where people are closer to the station and better served, but shift markedly in

peripheral and eastern AMP municipalities, where needs are high, and access is low. These areas, shown in red to yellow, emerge as the most structurally underserved when both demand and needs are considered simultaneously. From a PT perspective, they represent priority locations for

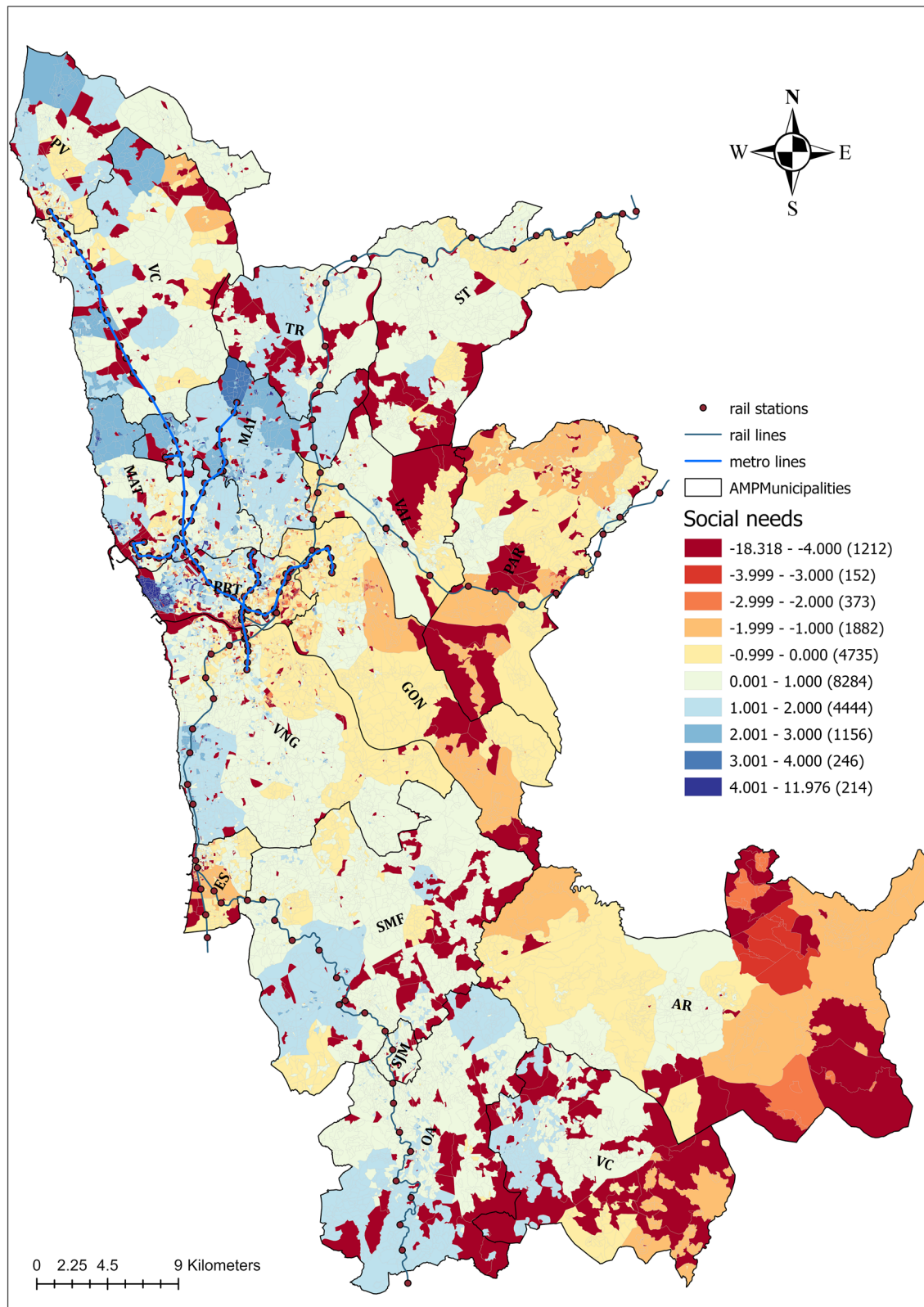


Fig. 7 | Needs distribution. The figure shows the spatial distribution of social needs across AMP subsections, allowing identification of low- to high-need areas. Red areas indicate the highest levels of social need, orange and yellow areas indicate

intermediate levels, and light to dark blue areas indicate comparatively lower levels of social need. Rail stations, rail lines, metro lines, and municipal boundaries are included as reference features.

additional bus routes, increased frequencies, or new multimodal integrations that extend the functional reach of the rail network. Conversely, the blue areas with low inequity values have relatively lower potential captive demand and may be better served by lower frequency buses or more flexible

transport systems, such as demand-responsive transport (DRT) or shared taxicabs, which can be integrated with the rail network.

Taken together, horizontal, vertical, and diagonal equity reveal complementary dimensions of inequity. Horizontal equity shows

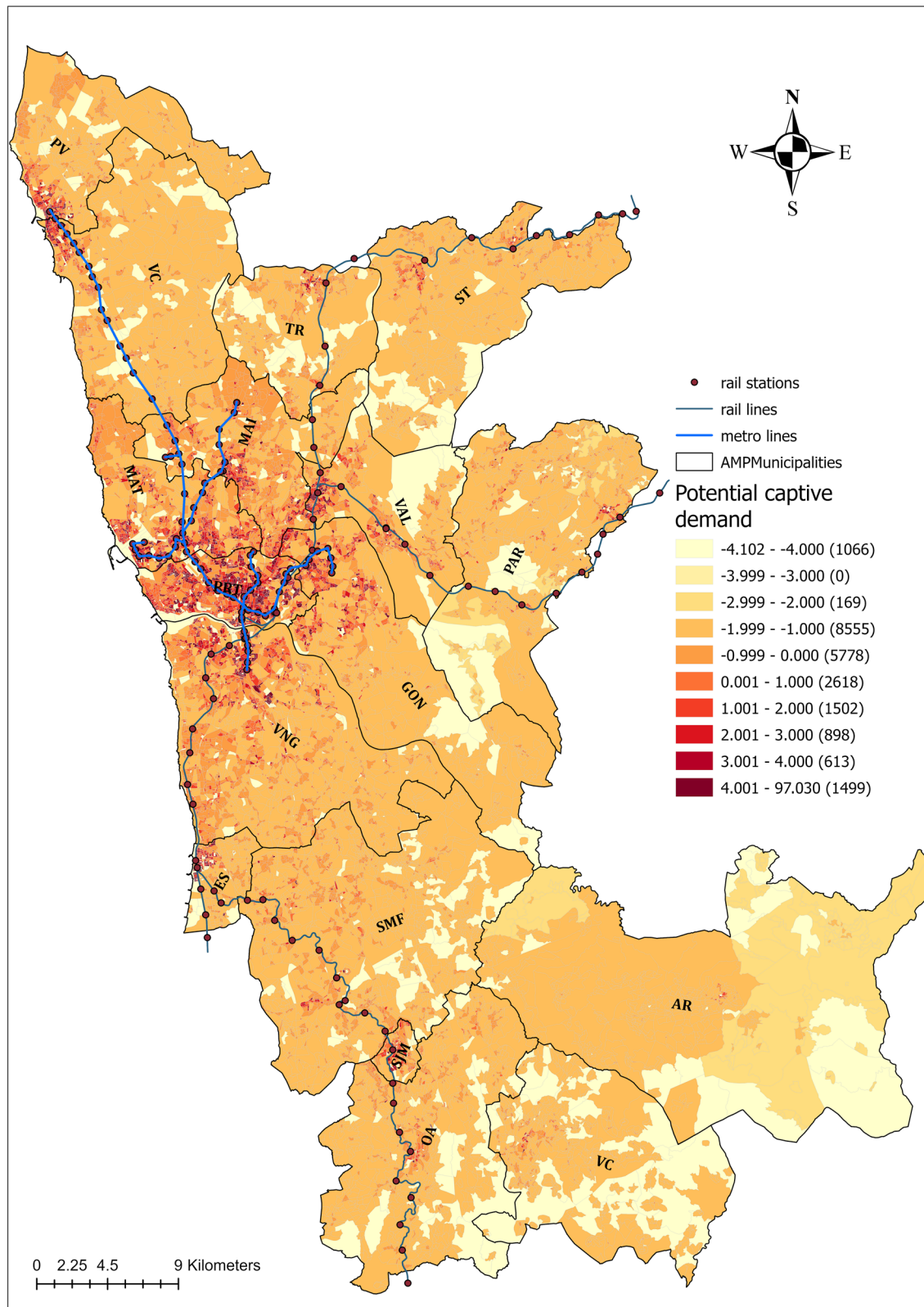


Fig. 8 | Potential captive demand distribution. The figure presents potential captive demand, which combines potential demand and social needs into a single indicator of likely dependence on public transport. Light beige areas indicate low

captive demand, whereas darker orange and red areas indicate locations where both demand and social needs are high. Rail stations, rail lines, metro lines, and municipal boundaries are shown for reference.

where population-driven demand is mismatched with supply; vertical equity highlights where socially vulnerable groups are underserved; and diagonal equity synthesizes both, identifying zones where improving PTS provision would yield the greatest benefit

under a prioritarian framework. These results demonstrate that targeted interventions—particularly in eastern and suburban municipalities—could substantially advance equity in access to PT across the AMP.

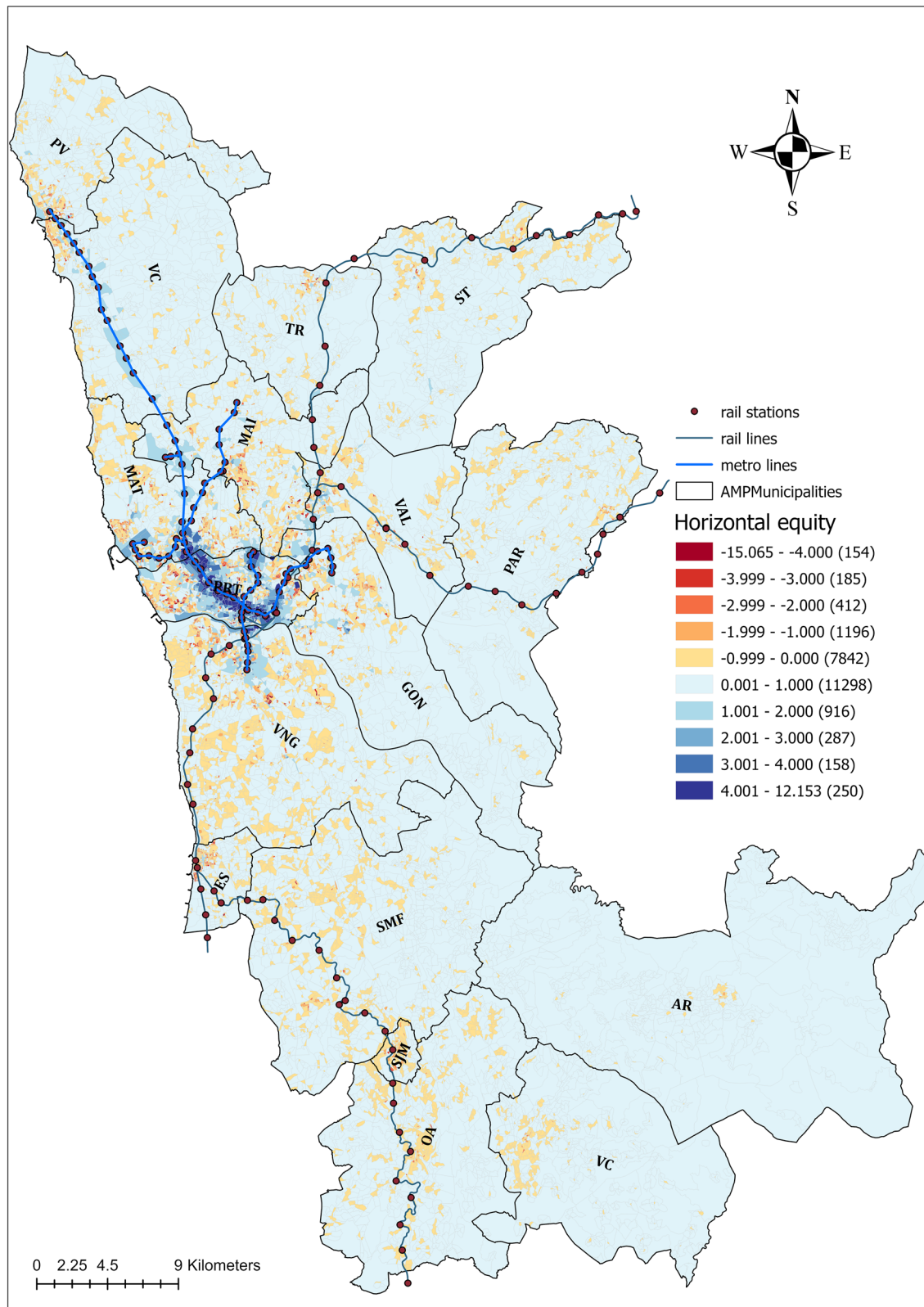


Fig. 9 | Horizontal equity in walking access to PTS. The figure illustrates horizontal equity in access to public transport services (PTS), defined as the gap between walking accessibility and potential demand. Red, orange, and yellow areas indicate

negative values where accessibility falls below demand, while light to dark blue areas indicate positive values where accessibility exceeds demand. Values near zero represent a balance between accessibility and demand.

Discussion

This paper evaluated walking access to PT stations in the AMP and examined inequities in service access through horizontal and vertical equity, as well as the newly proposed diagonal equity. While

horizontal equity emphasizes equal distribution of PTS across the region for everyone, aligning with population potential demand, vertical equity captures mismatches in need-based provision of PTS. Although both concepts have been widely used by researchers, these

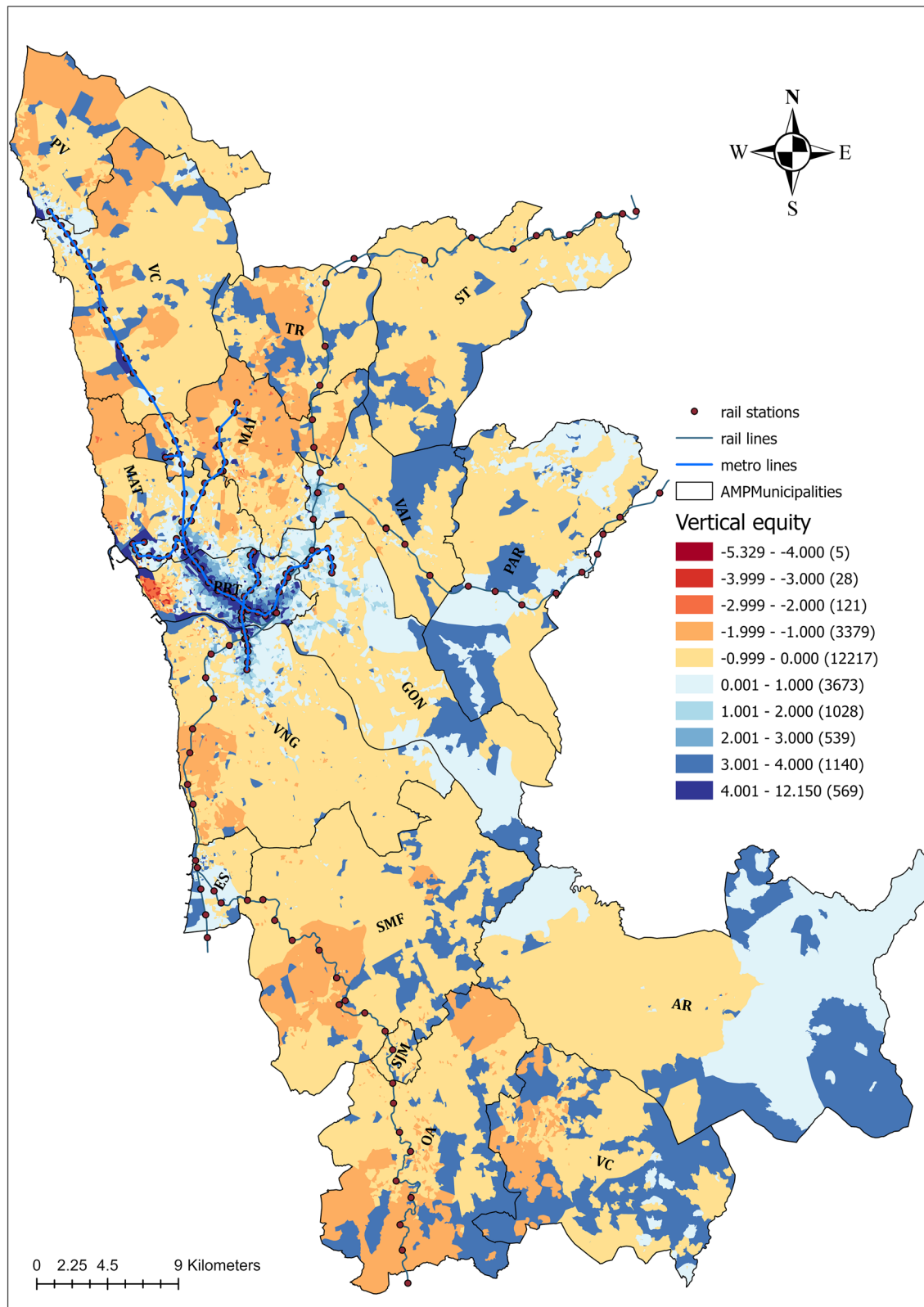


Fig. 10 | Vertical equity in walking access to PTS. The figure shows vertical equity, defined as the gap between walking accessibility and social needs. Red, orange, and yellow areas identify locations where accessibility to public transport services (PTS)

is insufficient relative to social needs, whereas light to dark blue areas indicate accessibility levels that exceed the measured needs. Values close to zero represent a balance between accessibility and needs.

measures often lead to contrasting and incomplete assessments when used independently. The key contribution of this paper is the introduction of diagonal equity, a composite measure that balances the two approaches, incorporating the essence of both horizontal and

vertical equity, offering a more holistic and actionable framework for identifying inequities in PT access.

To define the PT supply component, we estimated access to the nearest PT stations using a gravity measure. This measure incorporates the physical

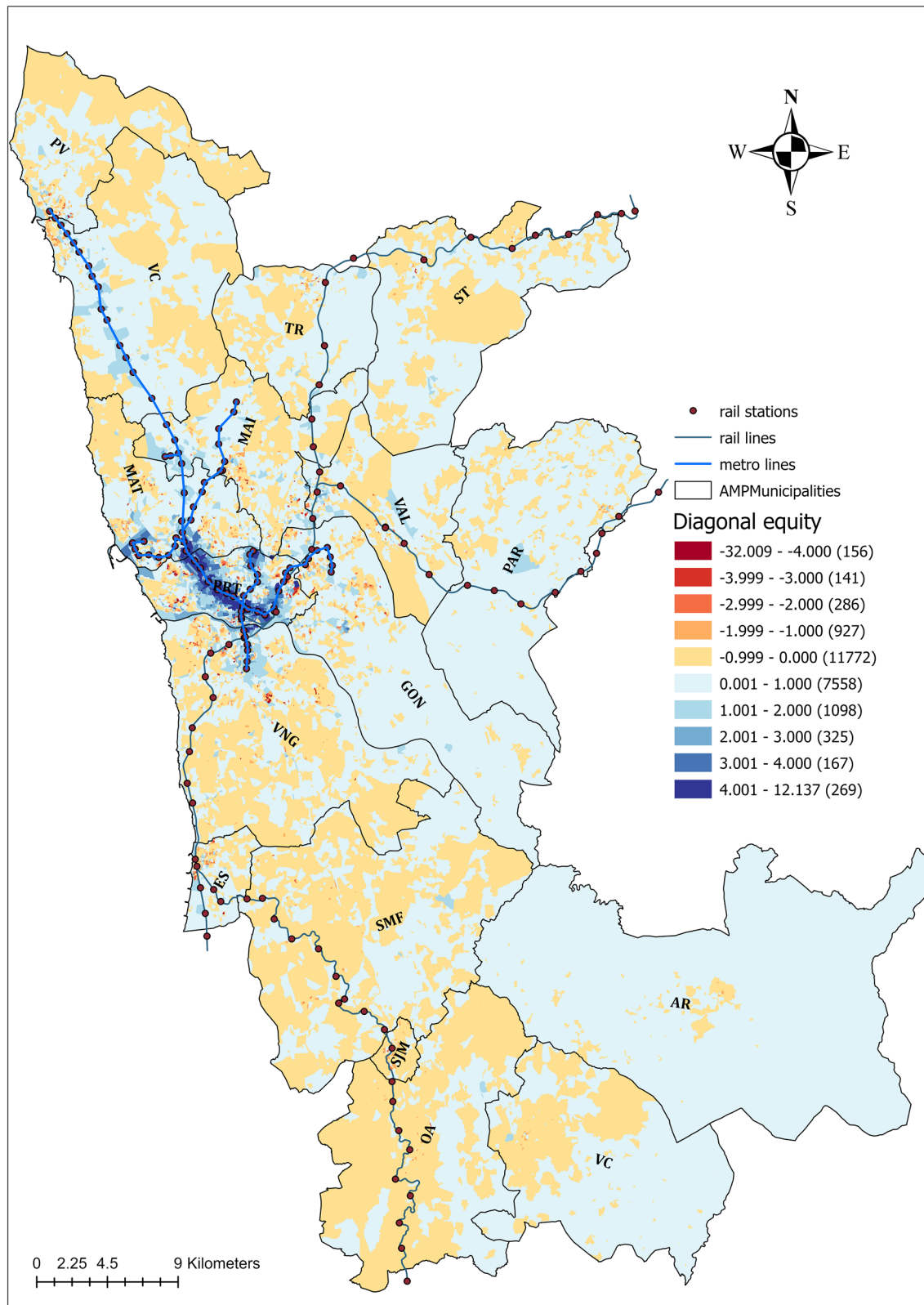


Fig. 11 | Diagonal equity in walking access to PTS. The figure presents diagonal equity, defined as the gap between walking accessibility and potential captive demand. Red, orange, and yellow areas indicate locations where accessibility to public transport services (PTS) is insufficient to meet the combined demand-and-

needs measure, while light to dark blue areas indicate accessibility levels exceeding potential captive demand. Values near zero represent a balance between accessibility and captive demand, highlighting areas where service provision aligns with both population demand and social needs.

separation between census blocks and rail/metro/bus stations in terms of walking distance/time, an impedance coefficient, and the attractiveness of the stations. The proposed accessibility framework should be interpreted as a network entry accessibility diagnostic, complementary to but not a substitute for comprehensive activity-based or end-to-end accessibility analysis. Next, using demographic data from the Census 2011 and socioeconomic variables obtained from INE, we employed PCA to identify the principal components and their correlations among these independent variables, which enabled the estimation of potential demand and needs for each census block. The product of these two yielded the potential captive demand measure representing the subset of the population most likely to depend on PT, which underpins the diagonal equity framework.

The equity assessment highlights clear distinctions among horizontal, vertical, and diagonal equity patterns across the AMP. For horizontal equity, higher inequities were more visible in urban areas and suburbs with high population density, where walking access to stations diminishes with an increase in distance. Southeastern municipalities with lower population density exhibit lower inequities due to lower demand. Vertical equity revealed a different pattern: areas closer to PT stations have low inequities because they tend to have lower needs and are more developed with better economic conditions. At the same time, disadvantaged neighborhoods and car-constrained households in eastern and peripheral municipalities exhibit the highest needs yet receive inadequate PT service. People's transport choices are influenced by their mobility needs, which are dependent on their socioeconomic status. Higher-income households in central and suburban areas typically have good transit access or private cars, while lower-income neighborhoods—especially in outer municipalities—face limited mobility options, resulting in greater inequities⁸. Parts of the AMP constituting well-served urban corridors performed well on both horizontal and vertical equity, while outer municipalities remained the most underserved. Diagonal equity synthesized these dimensions and identified areas where both demand and need converge, where inequities are structurally highest. Notably, diagonal equity revealed underserved pockets even within some high-demand central zones of municipalities, as well as substantial needs-based inequities in low-demand suburban zones, beyond walkable access to PTS. Addressing these issues can facilitate the provision of alternative PT modes to connect people to the rail network. Areas with high to moderate inequities can be served using more flexible modes, such as buses with higher frequency, to satisfy the needs and meet demand. Meanwhile, areas with lower inequities can be served by the DRT system, helping to reduce inequities with low investment and flexible approaches.

Conclusions

These findings underscore that diagonal equity provides a more comprehensive and policy-relevant assessment than using horizontal or vertical equity alone. Because diagonal equity highlights where unmet need and potential demand coincide, it can serve as a practical decision-support tool for regional transport planning. This adds value to traditional equity measures and provides a mechanism to identify and reach all populations across the region with satisfactory service, focusing on the disadvantaged people with mobility needs. The proposed approach of distributing services not only has the potential to facilitate a transition from private cars to PT^{82,83}, but it also guides policy design and influences public investment allocation in PT modes, complemented by walking. This can be achieved through the following policy recommendations:

(i) *Tier 1—Network expansion and high-frequency corridors in critical inequity zones (lowest diagonal equity scores)*: Areas exhibiting the highest inequity should receive the highest priority for intervention and warrant major service investments. In dense urban environments, high-frequency bus services, new routes, and improved bus–rail integration are likely to generate substantial equity gains despite requiring relatively high investment costs. These interventions are expected to be most cost-effective because severe access deficits affect large populations with both high demand and high social need.

(ii) *Strengthen multimodal accessibility (low diagonal equity scores)*: Higher inequity zones with significant accessibility deficits but moderate captive demand beyond walkable rail access may benefit from feeder bus services and multimodal mobility hubs to enhance first-mile connections by linking local services to rail and high-capacity transit networks. These measures generally require moderate investment while offering considerable improvements in accessibility for vulnerable populations.

(iii) *Tier 2—Flexible and demand-responsive transport (moderate diagonal equity scores)*: In moderately inequitable zones, dispersed captive demand makes fixed-route services less efficient. The deployment of flexible modes such as DRT, shared taxis, or community shuttles offers favorable cost-effectiveness by matching supply to variable demand without overbuilding capacity. The diagonal equity framework can help identify locations where high social need coincides with dispersed travel demand, making flexible transport solutions particularly suitable.

(iv) *Tier 3—Frequency and reliability upgrades (higher diagonal equity scores)*: Areas already served but with residual inequities may only require targeted service adjustments, such as timetable optimization, modest frequency increases, or improved transfer coordination. These lower-cost interventions can help maintain equitable access while preventing the emergence of future disparities without major capital expenditure.

(v) *Decision support for investment prioritization and performance monitoring*: Diagonal equity scores provide a transparent, reproducible metric to guide regional funding decisions by highlighting locations where specific interventions—such as new routes, higher frequencies, or last-mile links—would yield the greatest equity gains relative to their implementation costs. Authorities can rank projects by equity impact per unit cost, directing resources toward Tier 1 interventions first, followed by Tier 2 and Tier 3 as budgets allow. As a consistent and reproducible indicator, diagonal equity enables public authorities and municipalities to monitor how service changes or policy interventions affect transport equity over time, shifting zones across tiers and enabling adaptive and data-driven planning.

(vi) *Enhance data resolution for future applications*: The effectiveness of intervention targeting can be further improved through the integration of higher-resolution socioeconomic, land-use, and mobility datasets, allowing planners to better distinguish between areas requiring major infrastructure investment and those where lower-cost operational or flexible mobility solutions are more appropriate.

The conceptual framework proposed in this study, including the potential captive demand measure and the diagonal equity perspective, was subsequently operationalized and empirically implemented in a companion study⁸⁴. In that study, the proposed potential captive demand measure was incorporated within a broader comparative assessment of different equity perspectives for public transport network design scenarios in the AMP case study, and their performance was evaluated in terms of service coverage, social equity, and technical efficiency. The results showed that network designs based on the potential captive demand consistently achieve higher technical efficiency scores while maintaining a more equitable service distribution. These findings provide empirical evidence for the practical applicability of the diagonal equity framework and confirm that it extends beyond a theoretical construct. Unlike conventional approaches that address coverage and equity separately, the proposed approach effectively captures the interplay between potential demand and underlying social needs, leading to network configurations that achieve a more balanced trade-off between coverage, efficiency, and fairness.

In conclusion, we reinforce that diagonal equity can be operationalized using standard demographic and transit data, offering planners a replicable, data-driven tool to guide investment, frequency setting, and network restructuring. By embedding diagonal equity into the design process, authorities can move beyond abstract equity goals to produce measurable, balanced systems that ensure fair mobility access for all population groups.

There were a few limitations to this study related to the available data and methodological scope. First, there was no official source for the geographic and rail/road network data, so this information had to be retrieved

from open sources in raw form, which may be prone to some errors, despite the refinements and corrections described in the study area section.

Second, demographic data were collected from an official source but were based on the 2011 census, as the data for the 2021 census were not available at the subsection level when this research was conducted. However, intercensal comparisons (2011–2021) show that the relative spatial distribution of population vulnerability remained highly stable (parish-level correlations > 0.99), supporting the robustness of our equity analyses. All data is aggregated at the subsection (census block) level, which prevents individual-level analysis. For missing values in socioeconomic information at the subsection scale, data on car trips, land values, and income, available at the parish level, were disaggregated and spatially distributed to the subsections to match the scale, as the demographic information may introduce minor variations. However, since we are analyzing equity at a geographical scale, these variations will not significantly affect our analysis results, as the socioeconomic and land characteristics do not change abruptly at lower spatial scales. The main contribution of this study lies in the development and validation of a methodological framework for demand- and needs-based spatial equity assessment, rather than in producing time-specific forecasts and incorporating travel behavioral perspectives. The proposed framework is transferable and can be readily applied to more recent datasets as they become available, without altering its conceptual or analytical structure.

Third, the assumption that higher car use indicates lower need may not hold universally, for instance, in cases of forced car ownership among low-income suburban households due to limited alternatives. While our PCD metric mitigates this by capturing demand from all population groups and social needs, we acknowledge that distinguishing voluntary from forced car dependence would require disaggregate travel survey data. Future research should integrate such data to refine the social needs index.

Fourth, the accessibility analysis considers only first-mile walking access to the nearest rail station and bus stop. Cycling was not included due to the fact that its modal share in Portugal remains negligible, accounting for only 0.5% of trips according to the 2011 census⁷⁸ and rising only marginally to 0.6% by the 2021 census⁸⁵. However, integrating feeder bus modes with rail becomes more relevant when assessing first- and last-mile access to final destinations. Future research could incorporate multimodal accessibility (walking, cycling, and feeder buses) to provide a more complete evaluation of PT network accessibility.

Building on the diagonal equity framework developed in this study, future research can integrate equity scores as an objective function to optimize the PT network design, including the strategic addition of new stations or lines to address identified gaps. Particular attention should be given to operationalizing the proposed tiered intervention framework, using diagonal equity scores to guide sequential investments and their cost-effectiveness. Finally, future work could enhance data input by integrating transit smart card records, land-use data, post-pandemic shifts, and travel surveys to capture actual ridership patterns and travel behavior, thereby improving the practical relevance of equity assessments for current planning decisions.

Data availability

The demographic and socioeconomic data used in this study were obtained from the Census database of the Portuguese National Statistics Institute (INE). Road network, rail lines, rail stations, and bus stop data were obtained from OpenStreetMap and BBBike extracts. Public transport service data, including routes, stop locations, and service frequencies, were collected from publicly available General Transit Feed Specification (GTFS) datasets provided by Metro do Porto and Sociedade de Transportes Colectivos do Porto (STCP). Data for UNIR bus services and Comboios de Portugal (CP) rail services were obtained from publicly available route schedules and timetables. The raw data sources are publicly accessible through the respective providers. The processed datasets, accessibility measures, and equity indicators generated and analyzed during this study are available from the corresponding author upon reasonable request.

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Author contributions

M.S. and A.C. conceptualized and defined the methodology of the study; M.S. performed the data collection, analysis and wrote the manuscript; A.C. reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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