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Assessment of integrated rail and bus transport network design: Equity and efficiency perspectives

Mudassar Shafiq [a,*], Marco Amorim [b], António Couto [a]

[a] Faculty of Engineering of the University of Porto, Rua Dr. Roberto Frias, s/n, 4200-465, Portugal
[b] Fraunhofer IAO, Fraunhofer Institute for Industrial Engineering IAO, Nobelstraße 12, 70569 Stuttgart, Germany

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ABSTRACT

Recognizing the vital role of public transport (PuT) in accessibility, inclusivity, and quality of life, its planning must balance efficiency with equitable service coverage. This study examines PuT network design, integrating rail and bus services while incorporating equity considerations for a more efficient and socially equitable system. Despite extensive research on PuT network design (PTND), balancing these objectives remains a key challenge in transit planning. This paper presents a methodological framework that integrates PTND with Data Envelopment Analysis (DEA) to design and evaluate multiple PTND scenarios. These scenarios are assessed using equity-based perspectives: potential demand (PD), adjusted demand (AD), and transport needs (TN). The approach identifies efficient designs that maximize service coverage and social equity, addressing varying population demands and needs. The methodology is demonstrated through a case study in the metropolitan area of Porto (AMP), offering policymakers insights into PuT equity implications for the infrastructure planning and decision-making process. Two output-oriented DEA models were developed: one using service coverage adequacy (SCA) as output and another incorporating both SCA and the GINI coefficient (equity) to assess the impact of different equity perspectives on system efficiency. Results indicate that network designs based on AD performed better with higher efficiency scores than PD and TN, suggesting that AD better captures PuT demand needs and supports equitable service distribution. The findings emphasize the need to integrate population equity perspectives and multimodal transport to create more balanced and efficient PuT systems, ensuring fair access to mobility for diverse populations in the region.

1. Introduction

Public transport (PuT) enhances accessibility and inclusivity, contributing to the quality of life by offering alternative travel options. Thus, planning, designing, and developing new infrastructure is vital, requiring a detailed evaluation of the proposed design solution in terms of operational and social aspects. Researchers have highlighted the need for integrated transit planning that ensures equitable access across various transportation modes. Equity considerations significantly underscore the importance of PuT in urban environments as a significant portion of the population, including young people, older adults, and marginalized groups, often referred to as disadvantaged population groups, cannot afford private vehicles and rely on PuT (Guo et al., 2023). This dependence is expected to grow with changing demographics, rapid urbanization, and population growth. However, current transit systems often fail to meet rising demand and needs for transport, resulting in spatial and social inequities that limit accessibility for the population (Martin et al., 2008; Mavoa et al., 2012). Addressing these disparities requires identifying population demand and needs, developing respective measures from social equity perspectives, and incorporating them into PuT planning and design.

A review of the number of systems worldwide showed a significant increase in ridership after introducing new rail lines in rural and urban areas (Scherer, 2010). Implementing new rail services in underserved or rural areas connected with the existing system significantly improved people's access to the job market (Fan et al., 2012). Network designs focused on rail services in higher-income neighborhoods have shown a reduction in commuting time for high-income groups and an increase in low-income areas (Khabazi & Nilsson, 2021). Network design principles have been used to create transit services that offer equitable

* Corresponding author at: Departamento de Engenharia Civil, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal.
E-mail addresses: mudassarshafiq10@gmail.com (M. Shafiq), marco.amorim@iao.fraunhofer.de (M. Amorim), fcouto@fe.up.pt (A. Couto).

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opportunities to vulnerable populations (Ferguson et al., 2012). Studies have evaluated existing transport systems from accessibility and equity perspectives (Camporeale et al., 2017; Li et al., 2021), examined the impact of new infrastructure on system accessibility and efficiency (Martín et al., 2004), and assessed service effectiveness (Chen et al., 2019). Although public transport network design (PTND) has been extensively studied from various perspectives, the challenge of achieving an equitable as well as efficient PuT system remains under-addressed in planning and design efforts (Bonner & Miller-Hooks, 2023). Efficiently designed PuT systems benefit users by maximizing service coverage and ensuring equity while supporting decision-makers and service providers by minimizing infrastructure development and operational costs. Achieving these goals requires a PTND process that meets current demands and cost-effectively addresses the population's diverse needs.

Social equity in PuT is primarily addressed through two equity types with often conflicting objectives: horizontal equity and vertical equity (Arellana et al., 2021; Azmoodeh et al., 2021; Litman, 2022; Mohri et al., 2021). The literature addressing equity issues in the efficient PTND lacks in achieving a balance between the conflicting equity objectives (Kim et al., 2019). This study addresses this gap by designing an equitable PuT network that incorporates the population groups' varying demands, social needs, and transport needs derived from travel patterns. The designed system must provide ease of access and adequate service to meet the population's demands and needs while simultaneously minimizing the investments and costs for operators through optimized network characteristics and frequency (C. Chen et al., 2017; Suguiy et al., 2020). Thus, the efficiency and effectiveness of the system are essential to evaluate if the system is meeting the design objectives and how well it is performing under the given set of inputs.

Using the Metropolitan Area of Porto (AMP) as a case study, this paper aims to (1) demonstrate the use of different populations' equity perspectives quantified in terms of their demand and needs in equitable access to PuT services, including stop locations, route layouts, and frequency; (2) present a new two-step methodology for generating hypothetical multimodal PuT network design scenarios that extends the existing rail network by strategically locating new rail stations and generating new bus networks under different design parameters. The design methodology prioritizes equitable coverage, ensuring accessibility that meets diverse population demands, social needs, and transport needs; (3) determine the network characteristics as inputs and service coverage and social equity as outputs for every design scenario; and (4) perform Data Envelopment Analysis (DEA) to identify the efficient design solutions. PTND scenarios are defined as alternative configurations of the transport network, evaluated to identify trade-offs between efficiency and equity. This proposed approach provides a foundation for selecting efficient PuT networks, which can be optimized at a micro level for street stop locations, route design, bus lines integration, and frequency setting problem.

The paper is structured as follows: section 2 presents a detailed review of the existing literature on PTND, equity objectives, and the application of DEA for efficiency analysis in various transportation contexts. Section 3 describes the methodology used to define demand and needs perspectives, generate rail networks based on these perspectives, and integrate bus stops to create a comprehensive PuT network. Following this, the study presents the results obtained from the analysis. Finally, we discuss the implications of these results and present the conclusions.

2. Literature review

2.1. Public transport network design (PTND)

The PTND problem is particularly challenging due to its non-linear, multi-objective nature, encompassing numerous dimensions with conflicting goals and constraints, all within the complexities of an urban environment (Camporeale et al., 2017). It often involves sub-problems related to strategic, design, and operational decisions (Desaulniers & Hickman, 2007).

PTND has been addressed by adopting various approaches broadly categorized into mathematical optimization, heuristics, and metaheuristics. While mathematical optimization methods provide exact solutions, they are limited to small networks with ideal conditions due to their inability to handle the complexities of medium to large networks (Schöbel, 2012). Although heuristic techniques are capable of generating feasible solutions, they do not guarantee optimal outcomes in the global or local search space (Baaj & Mahmassani, 1995; Islam et al., 2019). On the other hand, metaheuristics overcome these limitations by employing iterative mechanisms to explore large solution spaces and find near-optimal solutions. Common metaheuristic methods include Genetic Algorithms (Goldberg & Holland, 1988) and Simulated Annealing (Kirkpatrick et al., 1983). Zhao & Zeng (2007) developed a stochastic global search framework combining simulated annealing, tabu, greedy, and bisection search methods to minimize user and operator costs in large-scale transit networks. W. Fan et al. (2008) also used metaheuristics such as tabu search, genetic algorithms, and simulated annealing for the Bus Transit Route Network Design Problem. A hybrid coverage model was developed to expand service coverage and increase accessibility for strategic planning (Murray, 2003). To enhance multimodal integration, Cipriani et al. (2012) employed a heuristic approach to design feasible transit networks by connecting high-demand nodes not served by rail with bus routes, aiming to optimize overall network design. Route generation tasks in a PTND are complex combinatorial problems that cannot be solved manually. Jha et al. (2019) tackled the multi-objective Transit Network Design and Frequency Setting (TNDFS) problem by generating bus routes using an initial route set generation (IRSG) procedure combined with a Genetic Algorithm, followed by optimizing route frequencies. Wang et al. (2020) developed a hybrid optimization model for the Transit Route Network Design Problem (TRNDP), addressing the limitations of prior methods that relied on oversimplified assumptions. Their approach introduced a multi-level, multi-mode design framework comprising a skeleton, arterial, and feeder network. It is important to note that there is no universally optimal transit network structure, as its effectiveness depends on external factors such as urban layout, passenger demand, and transfer disruptions (Fielbaum et al., 2016). Optimized design solutions involve trade-offs between minimizing passengers' generalized costs and reducing transit agencies' operational expenses under given constraints. Operational costs usually depend on the number and length of routes, fleet size, and hours of operations (Iliopoulou et al., 2019).

In summary, the literature highlights the evolution of TNDP methodologies from analytical models to advanced metaheuristic techniques, enabling more robust and scalable solutions for complex urban transport networks. These developments underscore the importance of balancing computational efficiency with solution quality to meet the diverse objectives of stakeholders. Achieving effective PTND requires balancing passenger benefits with infrastructure costs, which can be accomplished by strategic planning and applying algorithms to refine initial network designs (Mahmoudi et al., 2024; Shcherbakov & Golubev, 2016). These designs can serve as a basis for route optimization, scheduling, and frequency setting.

2.2. Equity and PTND

Equity in transport is a multifaceted concept, with varying definitions and metrics used to assess the fair distribution of services across populations with diverse needs (Pereira & Karner, 2021; Thomopoulos et al., 2009). In transportation-related research, two types of social equity have been widely discussed and adopted, i.e., horizontal and vertical equity. Horizontal equity is based on egalitarian principles highlighting spatial inequalities and advocating for equitable resource allocation and access to services among individuals or groups. However, horizontal equity overlooks existing inequalities, prompting the adoption of vertical equity, which considers disparities among groups with varying needs and potentials (Bertolaccini, 2013; Bonner & Miller-Hooks, 2023). Social equity goals often conflict when viewed through the lenses of widely used horizontal and vertical equity (Hrelja et al., 2024; Litman, 2022). Horizontal equity focuses on distributing resources equally among all individuals or groups, prioritizing the placement of stops in high-demand areas that generate more revenue for the operator. In contrast, vertical equity emphasizes the fair distribution of resources to disadvantaged individuals or groups with varying needs, often resulting in higher costs and lower financial returns (Di Ciommo & Shiftan, 2017). Horizontal and vertical equity assessments consider demographic factors such as population size, density, and age, as well as socioeconomic characteristics such as income and employment status (Y. Chen et al., 2019; Kaplan et al., 2014; Mohri et al., 2021). Other variables, such as student and employed populations, are also considered when evaluating equity (Davidson & Ryerson, 2021; Scott & Marshall, 2019). Equity reviews carried out by (Di Ciommo & Shiftan, 2017; Pereira et al., 2017; Pereira & Karner, 2021) highlighted the principles of utilitarianism and Rawlsianism, identifying that the particularities of the people and the characteristics of the transport system should be better understood and defined, thus addressing their capabilities. Social equity assessments, in particular, focus on socioeconomic indicators such as income, education, residential location, and housing costs, sometimes extending to employment status and welfare benefits, which directly impact social standing (Shafiq et al., 2024b; Zhu & Shi, 2022). Furthermore, car availability and usage are essential determinants of equity as they shape mobility needs (Cohen, 2020; Sun & Thakuriah, 2021). Population associated with these demographic and socioeconomic backgrounds are referred to as disadvantaged population groups in this study. In addition to individual components, the living environment and conditions related to transport and mobility, such as public transport, walkability, integration, spatial distribution, etc., significantly influence the population's capability level, having an even more substantial impact on low capability population groups (Azmoodeh et al., 2023b, 2023a). Incorporating these factors into the planning and design process can significantly improve the capabilities of the low-capability groups and enhance social equity. In summary, different characteristics and capabilities of the population address the different equity perspectives:

1. horizontal equity: the total population as the potential demand for PuT.
2. vertical equity concerning social needs: employment, income, and car ownership of the population characterizing their ability to afford private transport; thus, low-income population's needs and reliance on PuT.
3. diagonal equity: populations' adjusted demand to balance potential demand and social needs, achieving tradeoffs between horizontal and vertical equity objectives.
4. vertical equity concerning transport needs: characterizing the population's travel demand and their ability based on the demographic groups, income, car ownership, and usage.

Incorporating equity measures into PTND has also gained attention, with researchers emphasizing the need to balance costs with equitable service distribution. Fan & Machemehl (2011) used a bi-level optimization model to solve the network design model incorporating spatial equity as a constraint. A GA-based solution procedure was developed in this context. Kim. M, et al. (2019) also organized a bi-level transit route network design model based on the route network decision-making process considering equity as travel time savings. Equity goals can be achieved by strategically adjusting the location of the stops and service frequencies to better serve the population. Moreover, considering the ease of access, locating new stops is crucial for ensuring horizontal and vertical equity measured as horizontal and vertical equity by maximizing population and their points of interest coverage with a feasible number of stops (Giuffrida et al., 2022). Similarly, Ruiz et al. (2017) accounted for all system elements—routes, bus stops, frequencies, headways, and population needs to optimize service levels and ensure social and spatial equity, which was measured using the GINI coefficient. Camporeale, R. et al. (2018) developed a model that quantitatively incorporates spatial and social equity principles using the GINI coefficient as a constraint measure in the Transit Network Design Problem, proposing a starting candidate route set generation procedure to minimize the users' and operators' costs. However, achieving equity often incurs additional costs, highlighting the trade-offs in equitable transit planning (Camporeale et al., 2019).

In multimodal PuT systems, rail networks serve as the backbone, connecting with other modes to provide faster access across metropolitan areas, reshaping urban mobility and influencing urbanization patterns (Lunardon et al., 2023). Spatial placement of transit stations directly affects accessibility, population distribution, urban development, and transport related inequalities (Turbay et al., 2024). Moreover, access to rail systems benefits disadvantaged population groups by offering an alternative to car travel, potentially reducing road congestion (Dröes & Rietveld, 2015). However, the effectiveness of rail systems in delivering these benefits depends on network layout and the ease with which passengers can switch between transportation modes. Approaching PTND focusing on addressing different equity objectives is critical for generating solutions that can be evaluated for efficiency at a macroscopic scale, balancing costs and benefits. Differences in spatial efficiency among PuT agencies are primarily due to their success or failure in network planning and design (Georgiadis et al., 2024). The context and goals of strategic transport planning include network design, station locations, and frequency setting (Guihaire & Hao, 2008), which should mainly improve the quality of services, achieving equitable outcomes and economic efficiency (Caggiani et al., 2017; Chen et al., 2017). This study focuses on this strategic aspect of PuT planning, aiming to design multiple network solutions for rail systems and integrated bus stops. The key objective is to support policymakers in evaluating and comparing the efficiency and social benefits of different regional PuT investment options.

2.3. Performance assessment

Aiming at performance assessment and efficiency analysis, several methodological approaches have been employed in transport research, including multicriteria decision-making (MCDM), Analysis Hierarchy Process (AHP), and cost benefits analysis (CBA) (Keshavarz-Ghorabaee et al., 2022; Nassereddine & Eskandari, 2017). MCDM was used to identify sustainable transport alternatives for policymaking (Büyüközkan et al., 2018), AHP was explicitly adopted to evaluate the overall performance of the urban bus system and development of benchmarking of PuT systems (Jasti & Ram, 2019) as well as attempting to incorporate different principles of equity in transport evaluation (Thomopoulos et al., 2009). The CBA framework was used in transport appraisal to analyze accessibility gains and their effects on equity (Martens & Di Ciommo, 2017). Although these approaches are able to rank alternatives by making a comparison between different criteria variables with assigned weights based on their significance from past data or expert opinions, they lack in terms of determining the system's overall efficiency.

DEA, a non-parametric method, evaluates the efficiency of various comparable solutions referred to as Decision-Making Units (DMUs) simultaneously by analyzing multiple inputs and outputs without relying on subjective judgments. The DEA method has been extensively used to assess the efficiency of PuT systems. For instance, Georgiadis et al. (2024) utilized DEA to evaluate European multimodal systems considering a set of n PuT systems as DMUs, while Hilmola (2011) highlighted its role in benchmarking efficiency in large cities, emphasizing the need for effective space utilization. DEA has also been used as an appraisal tool to select different route options (Caulfield et al., 2013) and compute each bus line's operational efficiency and spatial effectiveness scores (Lao & Liu, 2009). Georgiadis et al. (2014) analyzed the bus system efficiency by evaluating resource productivity and the balance between supply and demand using DEA models. They utilized two models, efficiency and operational effectiveness models, route length, span of service, and scheduled frequency as service inputs, as well as revenue seat-km and passengers as outputs. Rezaee et al. (2016) incorporated operational inputs such as round-trip distance, number of bus stops, annual vehicle hours, population demographics for spatial input, and annual ridership as outputs to assess urban transport efficiency. Similarly, Roháčová (2015) used DEA to evaluate urban PuT lines by transforming input parameters, such as stops and operational costs, into outputs, for instance, passenger numbers and environmental impact. Hahn et al. (2017) applied a network DEA model to Seoul's bus services, considering efficiency, equity, and environmental impacts. Fitzová et al. (2018) used DEA to compare urban PuT systems by considering three inputs (fleet size, staff, and energy costs) and a single output (passengers), and Chen et al. (2019) adopted the service area, service density, service frequency, and route diversity as inputs and accessibility as outputs to assess the bus system efficiency.

Freiberg et al. (2024) highlighted the need to bridge the gap between theory and practice by addressing shortcomings in equity and accessibility within transport planning. They advocate for a comprehensive pre-analysis to better evaluate and justify policy decisions and project prioritization. DEA's versatility is demonstrated in evaluating both efficiency and effectiveness. Suguiy et al. (2020) based their DEA methodology to evaluate urban PuT that combines two conflicting perspectives: the economic, represented by an efficiency index, and the social, represented by a satisfaction index, while Wang et al. (2022) explored equity and service effectiveness through DEA, the GINI index, and spatial analysis. DEA also aids in balancing cost control and equity challenges in rural areas due to the increasing demand and limited operations resources available and the need to deal with the inevitable tradeoffs among multiple objectives and criteria (Chen et al., 2017).

In conclusion, although the research incorporates the horizontal and vertical equity perspectives of the population used in the PTND problem, the literature lacks in achieving a tradeoff in their objectives. There is a need to address this gap in the early planning phase of the PuT system, which focuses on the demand and needs of the whole population by introducing new lines maximizing the coverage for a more inclusive and efficient design.

2.4. Study objectives and contributions

To effectively assess the equity impacts on the system efficiency in the PTND process, this study employed a comprehensive DEA approach. Unlike previous studies focusing solely on existing routes or specific modes, our analysis considers multimodal PuT systems efficiency from populations' equity-based perspectives. This paper aims to bridge this gap in PuT design by integrating equity in rail and bus network design. While research has adopted DEA to benchmark current network efficiency, our approach evaluates proposed network design for diverse population needs rather than just maximizing demand. We prioritize locating rail stations in high-demand and needs areas and applying a maximum coverage model to integrate bus networks with the rail system. This approach provides insights into the inputs and evaluates equity as an output, reflecting service adequacy and resource distribution among different population groups.

3. Methodology

In this section, we outline the proposed methodology for the PTND incorporating equity to generate multiple design solutions that maximize access to PuT services, and the population served. We also compare the proposed designs in terms of achieving efficiency and social equity goals. The research methodology starts by defining measures of potential demand, adjusted demand based on demand needs, and transport needs derived from the demographic groups, the socio-economic characteristics, and travel information of the population. These three measures representing different equity perspectives are then used to measure the effectiveness of the designed rail and bus system in terms of equity and service adequacy. Using the existing rail system as a base case, this methodology proposes different rail network layouts serving the areas with adjusted demand and transport needs, expanding the current network by extending the existing lines or introducing new lines. Taking these rail networks as fixed components, we developed a network design greedy heuristic using Python to propose new network designs for the bus system by generating bus stops integrated with the existing rail system under different design parameters. The defined heuristic algorithm generated PTND scenarios for the expanded rail and bus network. Finally, output-oriented DEA models, with one output and two outputs with multiple inputs, were used to assess their efficiency under different scenarios. The following subsections provide detailed information about each step of the methodology.

3.1. Measures of demand and needs

To design and evaluate the PuT system, we based our analysis on different measures for varying population demands and needs across the region characterized by their socioeconomic backgrounds and travel patterns. These measures give us different equity perspectives on how effectively the PuT system serves diverse populations and allow to identify the inequalities in the distribution of services. Different demographic groups and lower-income populations are particularly vulnerable to social exclusion due to inefficient design (Manrique et al., 2022), transport poverty, and suburbanization (Allen & Farber, 2020). For this purpose, the population, demographic groups, and socio-economic data from the census data are obtained to derive the different demand and needs measures.

3.1.1. Potential demand (PD)

PD is measured by the total global population residing in the area and varies according to its distribution in the smaller census blocks across the region. The total population helps assess the total demand for PuT and the demand share of private modes that can be attracted to the PuT system. It provides an assessment of the system regarding horizontal equity based on egalitarian principles, where everyone has equal rights to PuT services.

3.1.2. Adjusted demand (AD)

As discussed in Section 2.3, horizontal (demand) and vertical equity (needs) often conflict due to their differences in objectives. To achieve a balance between these two objectives and to enable a holistic analysis, we constructed an AD measure that considers demographic demand and social needs. It provides a more need-centric demand measure.

Each census block is characterized by the PD measure, mainly influenced by demographic characteristics, and the social needs measure, based on socioeconomic variables such as income, car usage, and household characteristics. The higher income, car ownership, rent values, and social demographic classification reflect a strong preference to use them. With their higher social status and alternate mobility options, the needs are lower; thus, the AD becomes zero. Conversely, the AD assumes the same value as the PD for maximum needs, indicating a higher reliance on PuT due to fewer mobility options. This approach allows policymakers and planners to achieve a tradeoff between vertical and horizontal equity objectives by prioritizing areas with limited mobility options and where PuT demand is likely to be higher.

3.1.3. Transport needs (TN)

Next, to account for the travel demand of the population, the travel data given by the origin–destination data of the reported trips in the region was incorporated in addition to the demographic and socioeconomic information. This information was also referenced at the subsection level, which indicates the population's need to travel and its magnitude within that subsection. Thus, this measure is referred to as transport needs (TN) as it signifies the need to travel and the people's ability for mobility.

3.2. Rail and bus network design

The PTND process consists of two design levels: the rail and the integrated bus network. Using the derived demand and needs measures, the study focuses on designing improved PuT networks that serve the areas with the highest demand and needs by the rail services and the remaining areas to be served by the bus system.

Step 1: As the rail system is the rigid structural component of the PuT system, it is not cost-effective to change the structure or location of the rail stations. Therefore, we consider the existing rail system, including the train and metro, the base scenario for future development and planning. We begin by focusing on extending the current rail and metro lines by locating new stops in the closer unserved areas with the highest AD and TN. For the remaining unserved areas, we created new rail and metro lines that follow the areas with the highest demand and needs. At the end of this process, the unserved areas were served with bus stops. We proposed different rail network structures: the base scenario consisting of the existing rail system, two scenarios for AD, and two for TN. These proposed rail networks will serve as a basis for generating bus stops integrated with the PuT system.

Step 2: For the second design level, considering the rail stops as starting points, an algorithm (see Annex A and B for the pseudo-code) generates stops and route lines based on the following set of parameters and constraints:

1. minimum population in the subsection
2. minimum and maximum distance between consecutive stops.
3. maximum number of stops per line.
4. population density to locate new stops.

The algorithm generates stops in two phases: initial and extra. First, it starts with the existing rail stop located in a subsection, searches in the neighboring subsections, and places a stop in the subsection if it meets the above criteria. It searches for a set of stops until it finds no more solutions. Then, for the remaining unserved subsections, the algorithm identifies the subsection with the highest population density as a starting point for the bus line and repeats the same process until no further solution is found. Bus stop spacing plays an important role in ensuring ease of access and maximized ridership. An average bus stop spacing is 400–540 m/stop in Europe and 160–230 m/stop in the United States (Devunuri et al., 2024; Reilly, 1997). For bus rapid transit, the average spacing is 758 m across 37 systems globally (Tirachini & Cats, 2020), with values ranging from 300 m to 1800 m. Based on the preferred walking distances to the bus stops for ease of access, we considered the minimum threshold value of 500 m (Shafiq et al., 2024a) and the maximum value of 2000 m and 5000 m to maximize the coverage in urban and suburban forms and improve the service quality of the bus system. Dixit et al. (2021) examined the concept of circuity in PuT design, which refers to the longer travel times associated with routes. Higher circuity not only leads to longer travel times but also increases costs for passengers, raising equity concerns. To address this, the algorithm has a constraint for the maximum number of stops, ensuring efficient travel times and better integration with the rail network. Different integrated bus networks are generated for every rail network based on the combination of the abovementioned constraints. Integrated rail and bus networks are collectively referred to as PTND scenarios. The flowchart for the proposed algorithm is illustrated in Fig. 1.

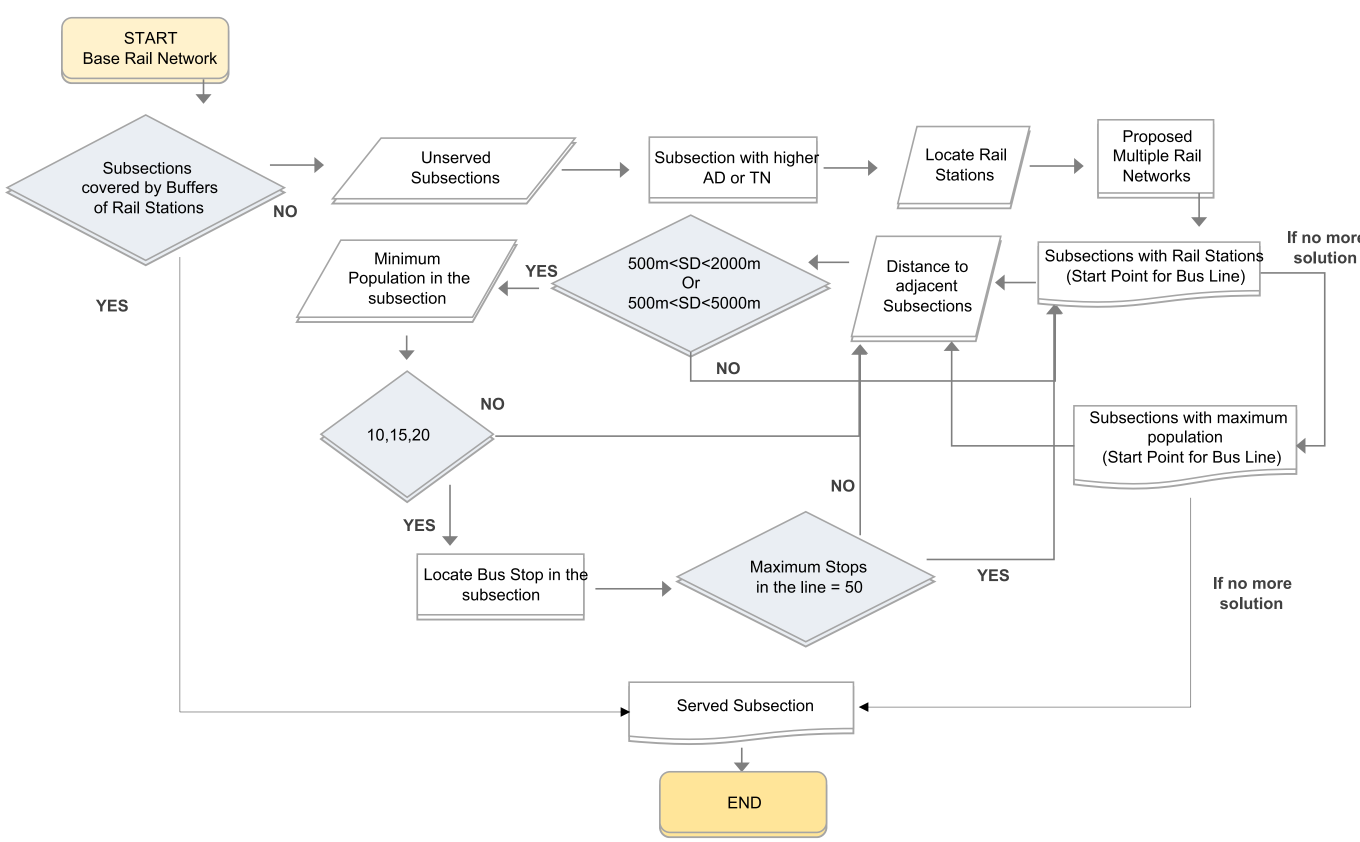

Fig.1. Algorithm flowchart for PTND.

3.3. PuT efficiency analysis using DEA

For output-oriented models, DEA helps to identify the most efficient DMUs based on the efficiency scores (φ) among several DMUs j (1,2,..,n) for given sets of inputs x (i = 1,2,..,m) and outputs y (r = 1,2,..,s).

Maximize $.\varphi$

$s.t.\sum_{j=1}^{n}\lambda_j y_{rj} \geq \varphi y_{ro}$;

$\sum_{j=1}^{n}\lambda_j x_{ij} \leq x_{io}$;

$\sum_{j=1}^{n}\lambda_j = 1$;

$\lambda_j \geq 0$.

Researchers have adopted it widely in transport research to help them in the decision-making process to choose the most efficient DMU with a cost-effective set of inputs such as network size, frequencies, and route and service diversity, resulting in maximized output in terms of accessibility, time savings, or the population served. This paper adopted the DEA method to analyze and evaluate the most efficient PTND scenario from the proposed network designs. The PTND scenarios proposed in the previous section established a set of DMUs (i.e., comparable proposed PuT networks) by considering different population equity perspectives. Consequently, each design scenario produced three DMUs: one aimed at the total population (PD), a second focusing on the population with limited resources for travel (TN), and a third addressing the population with a propensity or need to use PuT (AD). To perform the DEA, we adopted the following set of inputs and outputs:

3.3.1. Inputs

All the proposed networks resulted in a system with varying distribution of stops and routes. For the given distribution of stops in the urban and suburban areas, frequency requirements also change, resulting in different levels of the population served, service required to meet the demands and needs, and the associated costs. We considered the total length of the lines and total frequency at the stops as inputs in this study, as their extent and distribution determine the total cost incurred and benefits achieved.

Inputs = $Length_{mode}$ and $Numberofstops_{mode}{}^{*}.Frequency_{mode}$

As mentioned earlier, we categorized the PuT modes as metro, rail, and bus; thus, we have six inputs for every scenario.

3.3.2. Outputs

From a public policy perspective, the outputs should reflect the contribution of PuT to society and meet people's expectations. Two outputs were considered for equity and service coverage, defined by the GINI index and service *coverage adequacy (SCA)*.

GINI index: We adopted the GINI index, which provides a global index of equality in the region. This index allows to quantify and compare the equitable service distribution across the DMUs and scenarios. and Ji et al. (2024) also relied on the GINI index for equity assessment as it provides a nuanced perspective on transport quality. For this purpose, we performed a service area analysis to calculate the area served by walking and estimate the service levels shared among the population Eq. 1.

$PTS_i = \sum_n \frac{Area_{Bn}}{Area_{CT}} {}^{*} SL_n$ (1).

where, PTS_i is the public transport service for the CT i,

$Area_{Bn}$ is the total buffer area of stops n within each CT,

n is the number of walk access buffers for each stop/station in the subsection,

$Area_{CT}$ is the total area of the CT,

SL_n represents the service level given by the weekly frequency at stops n for PuT modes.

PTS provides the total service level available for the target population in the corresponding CT and is used to analyze the distribution of services among this population, as well as to assess its equity. It helps analyze how well the generated solutions improve the equity of the PuT system in the region from different equity-based population perspectives. The GINI index is estimated using Eq. 2,

$G = 1 - \sum_{i=0}^{n}(X_n - X_{n-1})(Y_n + Y_{n-1})$(2).

where:

X_n represents the cumulative proportion of the population, and Y_n represents the cumulative proportion of PuT supply.

The GINI index ranges from 0 to 1, with lower values representing greater equity and higher values indicating a more unequal distribution of services. Incorporating the GINI index as an output in DEA could inadvertently maximize inequities, as DEA aims to maximize outputs while minimizing inputs. To address this issue, we substituted the GINI index with its reverse and calculated it by subtracting the GINI value from one. By maximizing the reverse GINI value, the model effectively minimizes the original GINI index, thereby promoting greater equity in the distribution of services.

Service coverage adequacy (SCA): the second output we defined for this study is the new SCA measure, which reflects the extent to which the PTND effectively serves the potential population per stop. While the buffer areas around the stops provide an absolute measure of system coverage (Delbosc & Currie, 2011), SCA provides a better assessment of service effectiveness with the capacity to capture the population served by the proposed number of stops. Compared to GINI, which illustrates the equitable distribution of services across the population, SCA emphasizes the adequacy and efficiency of service coverage. This makes SCA particularly useful when evaluating whether the service coverage per stop is not only available but also efficient in achieving specific performance outcomes. The mathematical formulation of SCA is presented in Eq. 3. PTS was standardized between zero and one to obtain the public transport service index (PTSI), where a zero value represents no service, and one represents the maximum service available.

$SCA = \frac{\sum_{i=0}^{n}(PTSI_i{}^{*}Populationserved_i)}{TotalNumberofStops^{*}TotalPopulation}$ (3).

A higher value for SCA represents a higher service and population coverage.

As DEA evaluates how efficiently the inputs are converted into outputs, an output-oriented DEA model maximizes these outputs for a given set of inputs and provides efficient DMUs. Each DMU has been assessed based on its ability to maximize two outputs given six different inputs. It provides information regarding the most effective DMU by maximizing the output for the given inputs. Fig. 2 depicts the proposed methodological framework in this study.

3.4. Case study

The Metropolitan Area of Porto (AMP) in northern Portugal was selected as a case study for the implementation of the proposed methodology. The AMP area constitutes 17 municipalities with approximately 1.75 million residents, according to the 2011 census. As the country's second-largest metropolitan area, after Lisbon, the AMP constitutes a mix of densely populated urban centers and expansive rural areas. It creates a unique context for examining the varied transportation needs and design solutions required to serve such a diverse population. The AMP's diverse socioeconomic landscape allows for an in-depth exploration of PuT's demand and needs, making it an ideal setting for incorporating equity and access. Recent studies in the area have suggested the need for rail infrastructure developments and connectivity by motorized modes such as buses, as well as service improvements with PuT structure design for improved access and equity (Shafiq et al., 2024a, Shafiq et al., 2024b). The AMP area is divided into different spatial levels, the largest of which are municipalities, and the smallest census tracts are referred to as subsections, a total of 22,699. Population, demographic groups, and socio-economic data variables selected to quantify the demand and need measures were obtained for the subsections from the 2011 census (INE, 2011). The origins-destinations were derived from the 2017 Mobility survey conducted for the AMP, providing data on 80,314 trips (INE, 2018).

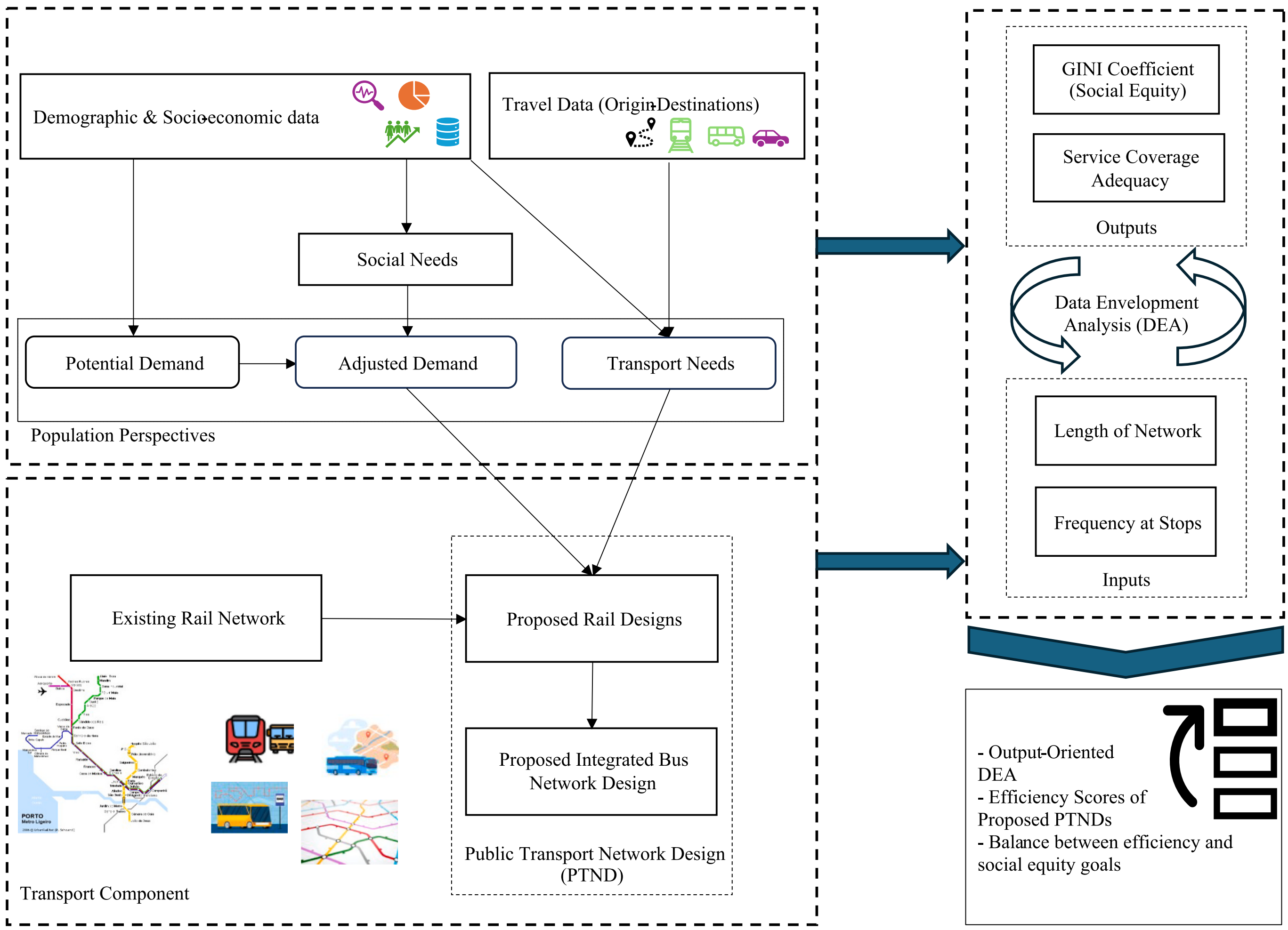

Fig. 2. Methodological framework of PTND inputs and outputs for DEA.

3.4.1. *Data collection*

Public Transport: In AMP, the metro network comprises seven lines that serve the central and northern municipalities of AMP, connecting them to Porto city center. Six lines are operational, while one line is under construction and will be operational in 2025. The train system comprises four broad-gauge and one narrow-gauge lines serving the north/northeastern and southern municipalities, also connecting them to Porto city center (Fig. 3). This census and transport data were used as a base for this study.

Census information: We selected a list of variables from the census data for the demographic considered disadvantaged population groups in the literature and socioeconomic information. This information helps determine the population's demand and needs.

i) Demographic information includes the total population, the female population, the dependent population (age groups under 15 years and over 65 years), the student population, the unemployed population, the population with welfare benefits, and house classification based on size and parking space.
ii) Socioeconomic variables, namely the average monthly income for individuals, monthly rent values, and private car share as a proxy for car ownership rates in the area.

Mobility Survey: In 2017, a detailed mobility survey was carried out in the AMP, utilizing both digital forms and in-person interviews, which collected data on around 80,314 trips (INE, 2018). Based on the travel information, we derived the origin–destination data, revealing the number of trips generated or attracted by each subsection and highlighting the associated travel demand and transport needs.

4. Results

4.1. *Rail and bus network characteristics*

Following step 1, as explained in the methodology Section 3.2, we generated four new rail networks in addition to the existing train and metro network referred to as the base rail network based on the AD and the population TN. The base network presents the details of the existing system, while the proposed rail networks include information about the new lines and stops proposed, and the base network represents the whole rail system. The new rail stations and line structures for the proposed PTND scenarios are shown in Figs. 4–7. The existing system is depicted in red, while the proposed extensions are depicted in yellow.

The network details, including the length of lines and the number of stops, are shown in Table 1.

Following this set of networks, we generated bus stops integrated with the rail system. For every network, the train and metro stops are the starting points for the bus lines. For the five rail systems, we generated 30 bus networks with the set of parameters defined in Table 2. The combined rail and bus networks are referred to as PTND scenarios.

For the PuT supply assignment, we classified the train, metro, and bus stops in the urban and suburban areas and assumed a service frequency accordingly. From the existing operational PuT system, we adopted the 90th percentile frequency values for the stops (Table 3).

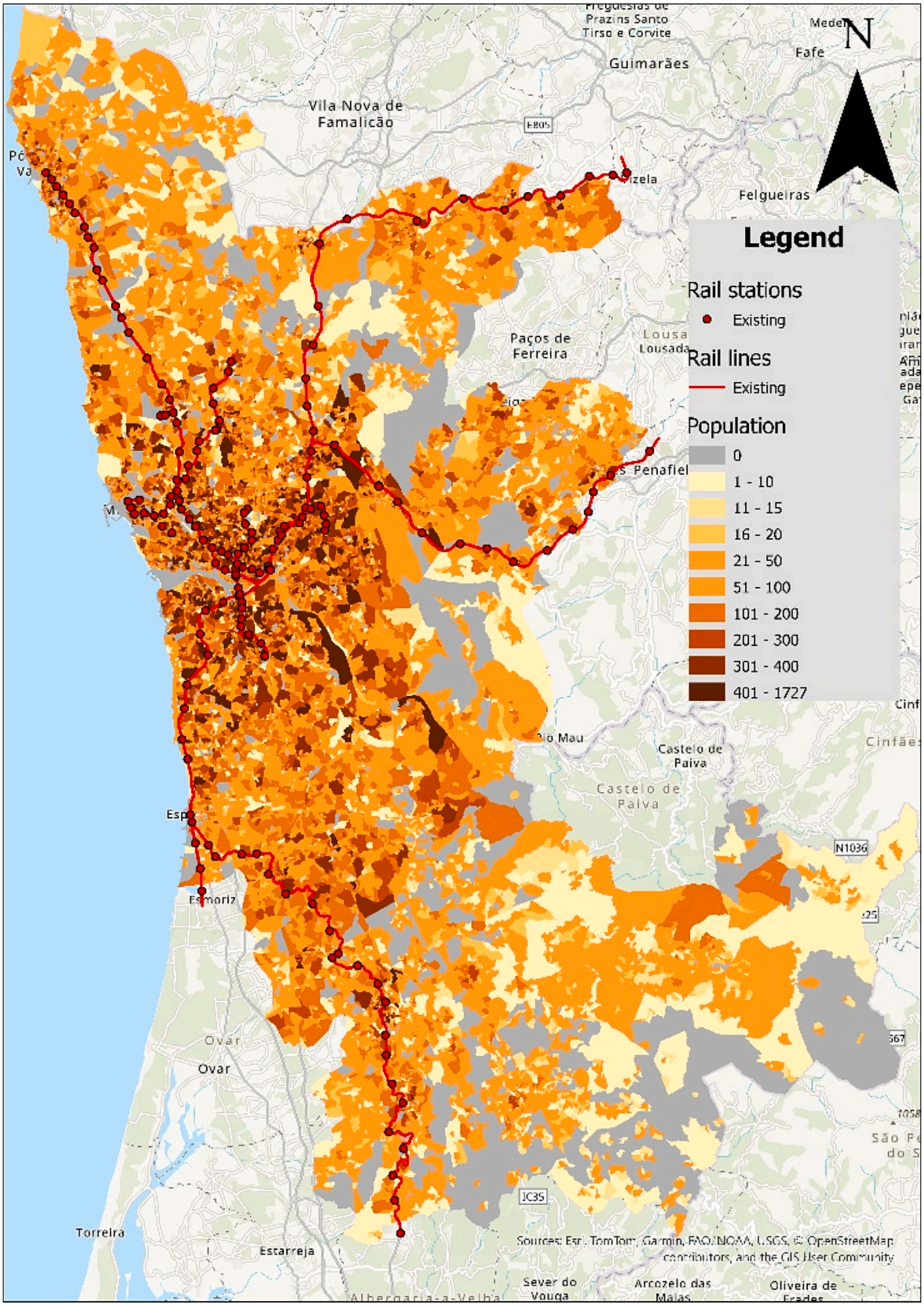

Fig. 3. Case study area and base case rail network.

Annex C presents the details of the bus lines and stops generated by the algorithm considering the base and proposed rail networks for improved intermodal integration. Network characteristics, such as the length of the lines, the number of stops in urban and suburban stops, and the required frequency at each stop for all PuT modes, including the train, metro, and bus, are considered input variables for the DEA efficiency analysis.

4.2. GINI and service coverage adequacy

Given the stop distribution for all the generated PuT networks, we performed the service area analysis and calculated the SCA for the total population to analyze the effectiveness of coverage and GINI value to assess how equitable the network is under different equity-based perspectives of PD, AD, and TN. Table 4 presents the obtained outputs for the design scenarios.

For the global population, scenario 9 provides the most effective

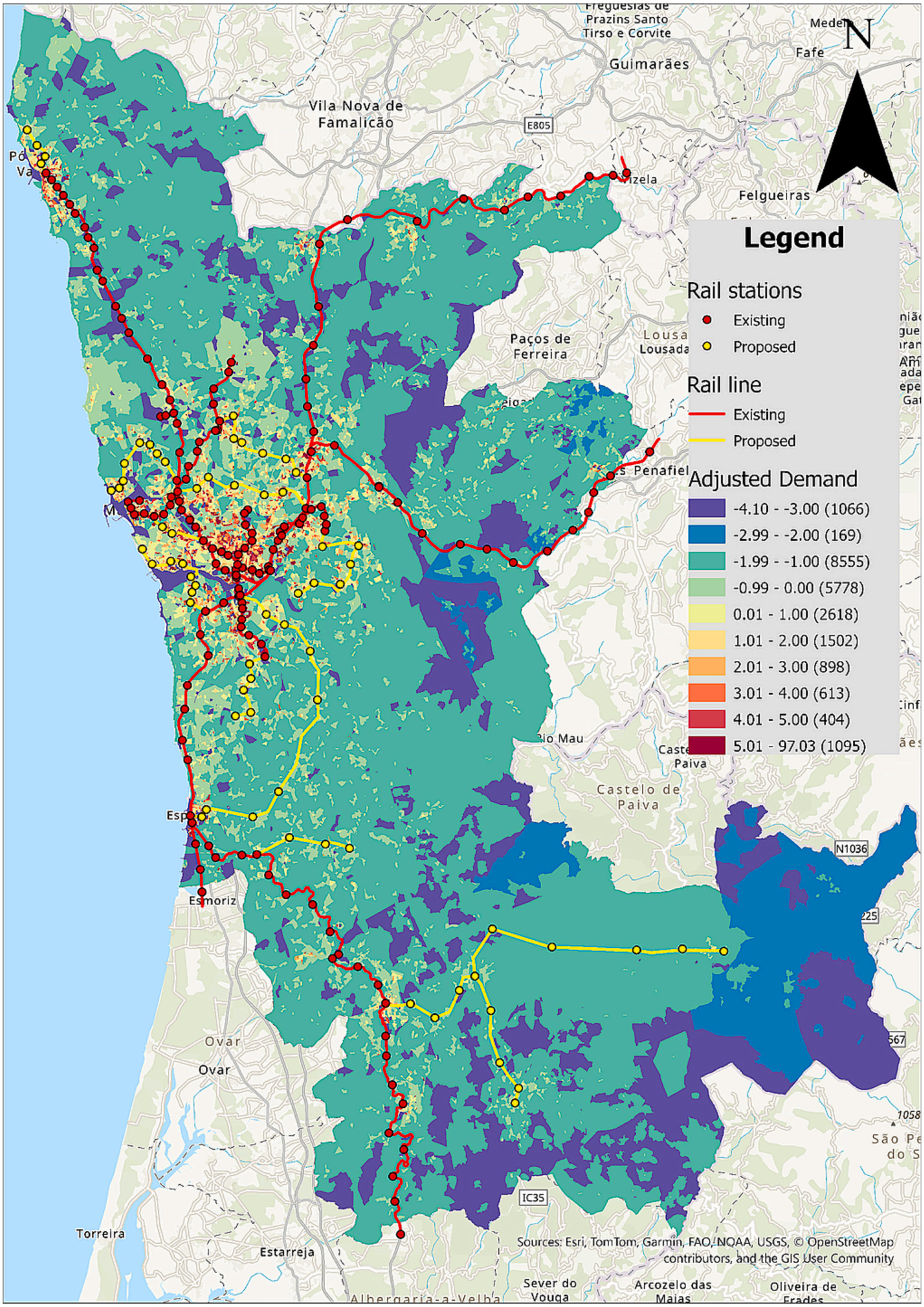

Fig. 4. Proposed rail network 2 for AD.

service coverage (0.2884), while scenario 4 is the least effective (0.1885). The results show that SCA values for the PTND scenarios for AD and TN are more effective in terms of coverage per stop. For the GINI coefficient, higher values indicate greater inequality, reflecting varying equity levels in meeting different equity-based population perspectives. From an equalitarian standpoint of the population (PD), the PTND scenario 25 is the most equitable with a GINI value of (0.3374), and Scenario 3 is the least equitable (0.3923). From the perspective of population propensity to use PuT in terms of their AD, the designed scenarios are more equitable, with lower values for GINI, ranging from 0.1570 in Scenario 28 to 0.2373 in Scenario 3. From the vertical equity perspective of TN, the PTND scenarios are slightly less equitable than AD, with Scenario 25 as the most equitable (0.1759) and Scenario 3 as the least equitable (0.2546). Overall, the values obtained for GINI suggest that PTND, by incorporating the AD balancing the demand and needs, reduces inequality.

From the global population in PD, the results reveal notable trade-offs between equity and SCA for the proposed PTND scenarios.

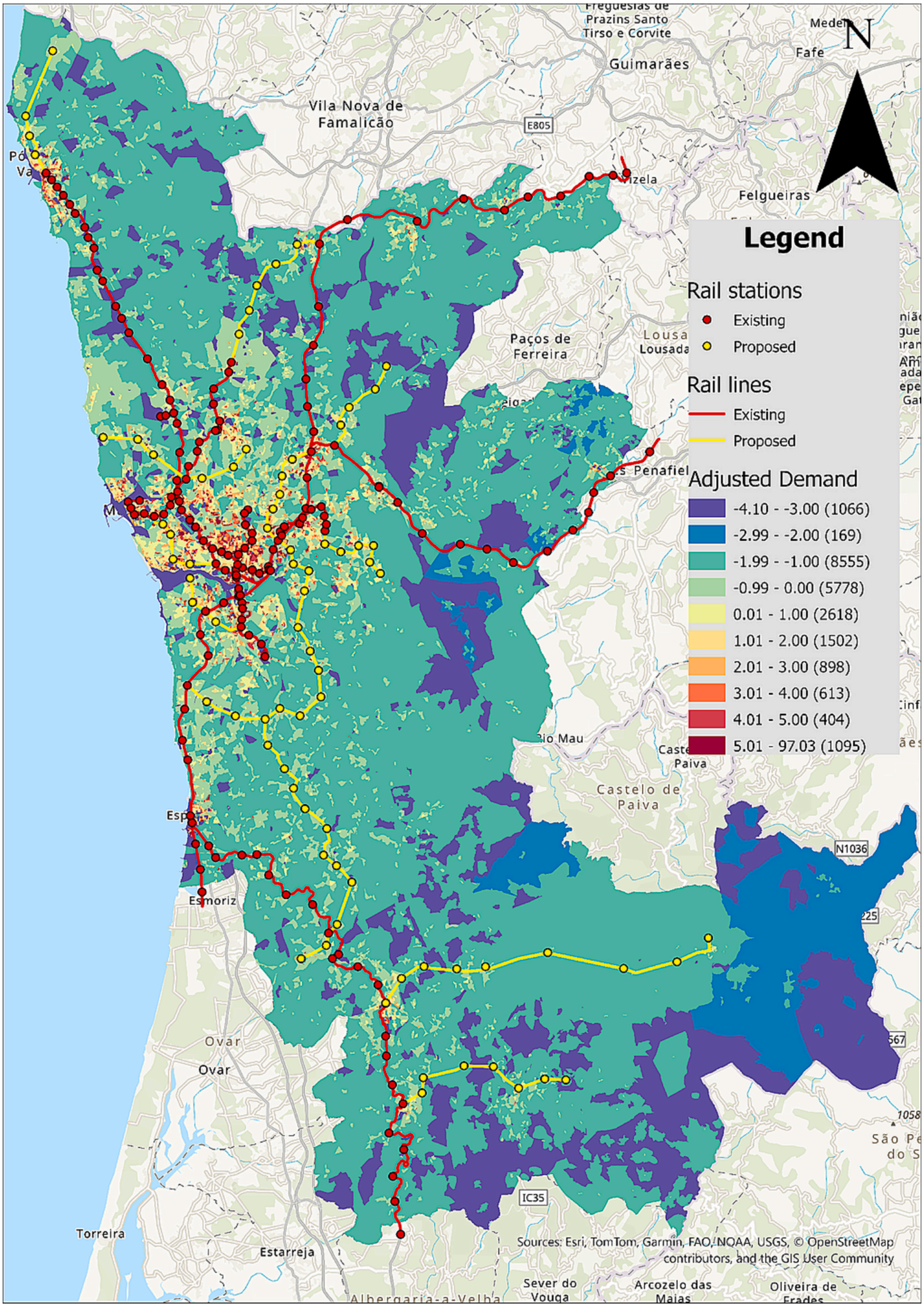

Fig. 5. Proposed rail network 3 for AD.

Scenario 3, with the highest GINI value of 0.3923, is less effective, showing a below-average SCA value of 0.2239. Scenarios 9 and 21, which also exhibit higher GINI values of 0.3814 and 0.3801, achieve better adequate service coverage for the global population with SCA values of 0.2688 and 0.2884. Conversely, scenarios 28, 25, and 29 demonstrate the lowest GINI values, 0.332, 0.3374, and 0.3376, reflecting more significant equity in transport allocation, with an average SCA value of 0.2316, 0.2429, and 0.2466. Scenarios such as 7, 8, and 11 strike a balance by achieving relatively higher SCA values of 0.2547, 0.2675, and 0.2583 despite not having the lowest GINI values of 0.3625, 0.3694, and 0.3598. In summary, the results highlight the challenge of balancing equity and efficiency in PTND, providing insights into scenarios that effectively address these trade-offs in achieving service coverage and equity objectives.

4.3. Efficiency scores for DMUs using DEA

Following the inputs and outputs results determined in Sections 4.1

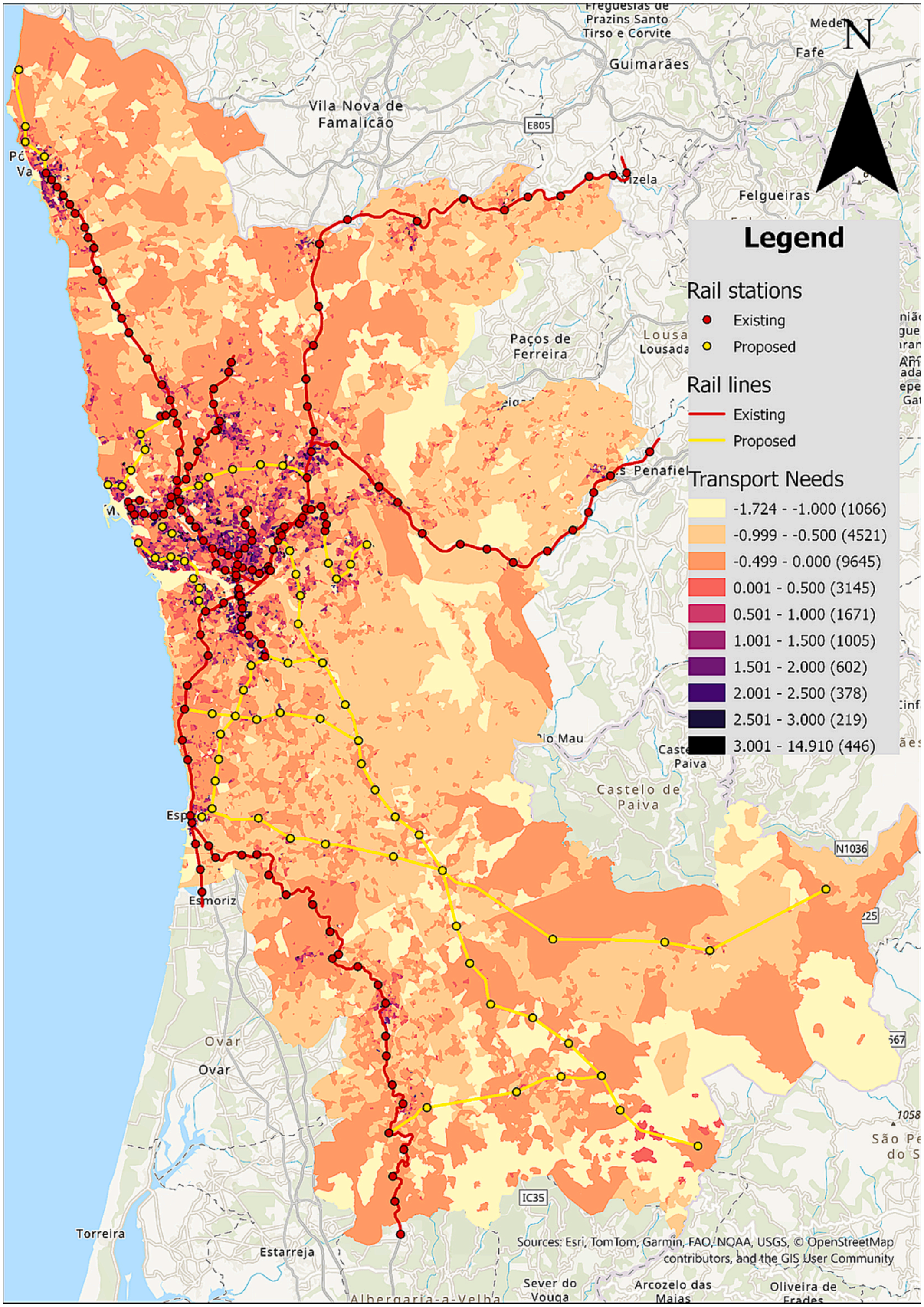

Fig. 6. Proposed rail network 4 for TN.

and 4.2, we selected the output-oriented DEA models to assess the efficiency of the proposed scenarios. Two DEA models were applied: one with a single output—SCA—reflecting a global population equalitarian perspective (PD), and another with two outputs—SCA and GNI—incorporating equity-based perspectives (PD, AD, and TN).

For the single output DEA, we considered 30 PTND scenarios as DMUs, using six inputs for network characteristics (Annex C) and SCA as the output. In the two-outputs DEA model, SCA and equity as outputs, while the same six inputs were used to assess the impact of equity on efficiency and compare DMU performance. For this, we based our analysis on 90 DMUs, each representing a PTND scenario from one of the three equity-based population perspectives. DMUs 1–30 used SCA and equity outputs based on PD, while DMUs 31–60 and 61–90 incorporated equity outputs GINI based on AD and TN, respectively, with the same inputs. Table 5 presents the DEA TE scores for both DEA models and detailed tables are provided in Annexes D and E.

DEA assigns a value between 0 and 1 for each DMU, which depicts technical efficiency (TE). The column next to each DMU in Table 5

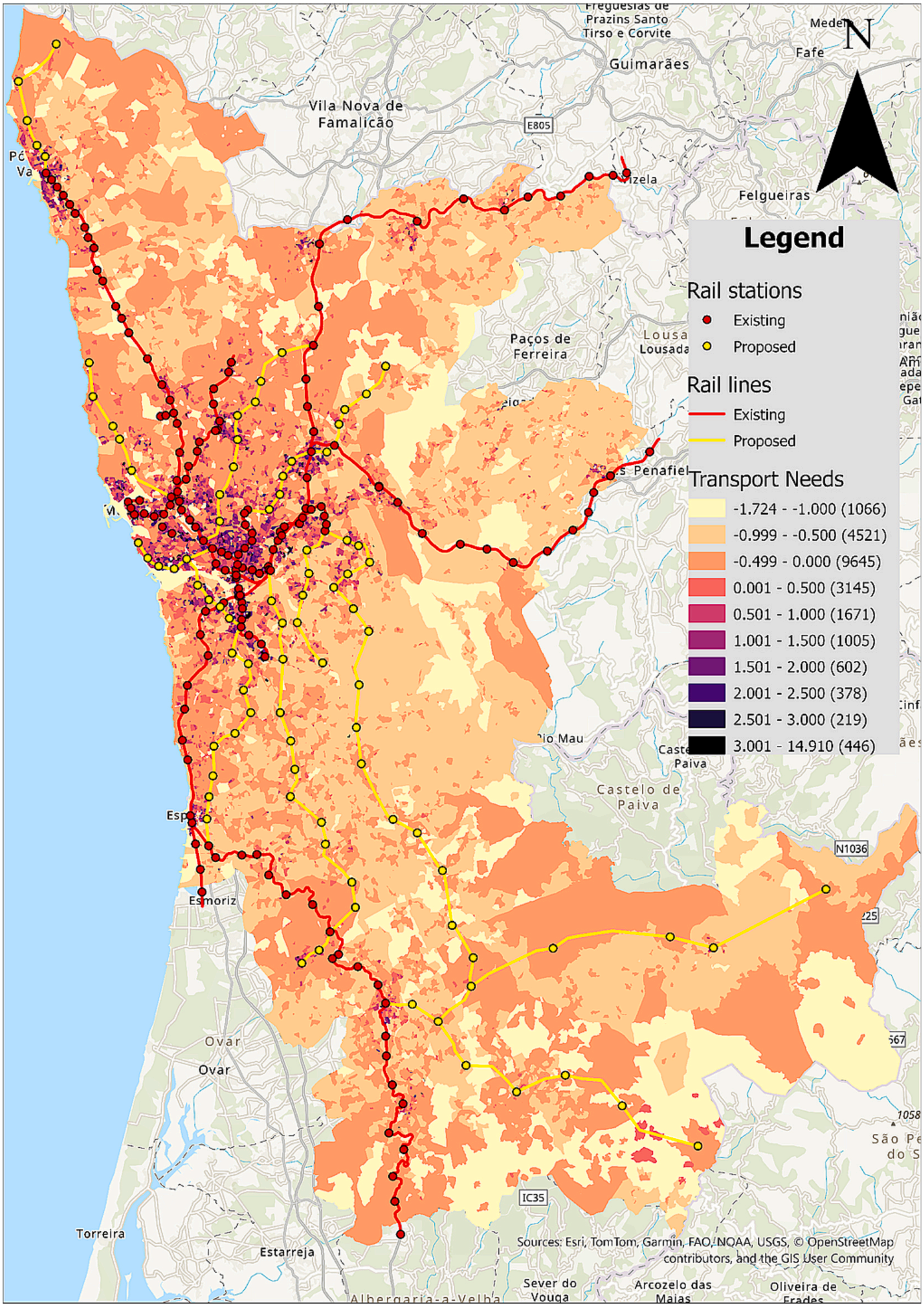

Fig. 7. Proposed rail network 5 for TN.

Table 1
Rail network characteristics.

	Number of train lines	Length of train lines	Number of train stops	Number of metro lines	Length of metro lines	Number of metro stops
Base Rail Network 1	5	152	72	7	74.7	87
Proposed Rail Network 2	9	216.23	96	15	130.81	131
Proposed Rail Network 3	13	253.65	121	12	112.16	115
Proposed Rail Network 4	11	194.66	115	13	115.53	115
Proposed Rail Network 5	11	285.64	121	14	147.25	130

Table 2
Bus design parameters.

Combinations	Stop distance interval	Minimum population (residents)
1	500 m < SD < 2000 *m*	10
2	500 m < SD < 2000 *m*	15
3	500 m < SD < 2000 *m*	20
4	500 m < SD < 5000 *m*	10
5	500 m < SD < 5000 *m*	15
6	500 m < SD < 5000 *m*	20

Table 3
Selected frequencies for different PuT modes.

PuT Mode	Classification	Assumed Weekly Frequency
Metro	Urban	3000
	Sub-Urban	1000
Rail	Urban	950
	Sub-Urban	400
Bus	Urban	1000
	Sub-Urban	500

Table 4
GINI and SCA for different population perspectives.

PTND	SCA PD	Gini PD	Gini AD	Gini TN
Scenario 1	0.1962	0.3697	0.2163	0.2335
Scenario 2	0.2089	0.3788	0.2249	0.2422
Scenario 3	0.2239	0.3923	0.2373	0.2546
Scenario 4	0.1885	0.3575	0.2037	0.2214
Scenario 5	0.1987	0.3657	0.2111	0.2290
Scenario 6	0.2137	0.3792	0.2231	0.2410
Scenario 7	0.2547	0.3625	0.1988	0.2108
Scenario 8	0.2675	0.3694	0.2053	0.2175
Scenario 9	0.2884	0.3801	0.2158	0.2279
Scenario 10	0.2441	0.3540	0.1908	0.2029
Scenario 11	0.2583	0.3598	0.1965	0.2085
Scenario 12	0.2747	0.3715	0.2076	0.2195
Scenario 13	0.2294	0.3480	0.1821	0.1996
Scenario 14	0.2440	0.3558	0.1893	0.2069
Scenario 15	0.2597	0.3659	0.1992	0.2167
Scenario 16	0.2196	0.3397	0.1745	0.1921
Scenario 17	0.2339	0.3459	0.1800	0.1977
Scenario 18	0.2514	0.3574	0.1915	0.2091
Scenario 19	0.2369	0.3644	0.2028	0.2149
Scenario 20	0.2511	0.3703	0.2081	0.2202
Scenario 21	0.2688	0.3814	0.2188	0.2310
Scenario 22	0.2276	0.3563	0.1955	0.2076
Scenario 23	0.2385	0.3621	0.2010	0.2133
Scenario 24	0.2584	0.3736	0.2119	0.2241
Scenario 25	0.2429	0.3374	0.1614	0.1759
Scenario 26	0.2578	0.3438	0.1668	0.1814
Scenario 27	0.2764	0.3537	0.1762	0.1908
Scenario 28	0.2316	0.3320	0.1570	0.1716
Scenario 29	0.2466	0.3376	0.1616	0.1763
Scenario 30	0.2628	0.3479	0.1705	0.1852

provides the efficiency score for that respective DMU. A score of "1″ indicates that the DMU is fully efficient in reaching its objective, meaning it is operating on the efficient frontier. A score less than "1″ indicates inefficiency, reflecting the proportion of outputs achieved relative to what could be achieved if the DMU were fully efficient.

For single-output DEA, DMUs 3, 9, and 21 have the highest TE score of 1, meaning that these PTND scenarios are the most efficient in terms of service coverage and capturing the population by the designed network. These DMUs are characterized by lower cost inputs such as network length, stops, and frequency, achieving maximized SCA. As discussed in Section 4.2, based on the results of GINI and SCA, there is a tradeoff in achieving a balance between efficiency and equity. The results, considering both equity and SCA as outputs, show that in terms of equalitarian principles of equity characterized by PD, the TE of the DMUs does not change. The system's effectiveness in service coverage across the population also achieves the equity goal of equal distribution of PuT services. The DMUs with an efficiency score of 1 in both cases are on the efficient frontier in the most productive way and generate the best outputs in terms of GINI and SCA.

Table 5
Technical Efficiency of DMUs from DEA.

Single output DEA		Two outputs DEA					
DMU	TE (SCA)	DMU	TE (SCA & Gini PD)	DMU	TE (SCA & Gini AD)	DMU	TE (SCA & Gini TN)
1	0.877	1	0.877	31	1	61	0.98
2	0.933	2	0.933	32	1	62	0.98
3	1	3	1	33	1	63	1
4	0.842	4	0.842	34	1	64	0.981
5	0.887	5	0.887	35	1	65	0.981
6	0.955	6	0.955	36	1	66	0.983
7	0.868	7	0.868	37	0.896	67	0.883
8	0.919	8	0.919	38	0.943	68	0.93
9	1	9	1	39	1	69	1
10	0.826	10	0.826	40	0.859	70	0.847
11	0.881	11	0.881	41	0.902	71	0.89
12	0.946	12	0.946	42	0.956	72	0.946
13	0.804	13	0.804	43	0.9	73	0.88
14	0.885	14	0.885	44	0.947	74	0.926
15	0.984	15	0.984	45	1	75	0.991
16	0.748	16	0.748	46	0.867	76	0.848
17	0.825	17	0.825	47	0.912	77	0.892
18	0.923	18	0.923	48	0.962	78	0.942
19	0.821	19	0.821	49	0.883	79	0.869
20	0.901	20	0.901	50	0.931	80	0.918
21	1	21	1	51	1	81	1
22	0.769	22	0.769	52	0.852	82	0.839
23	0.831	23	0.831	53	0.891	83	0.877
24	0.935	24	0.935	54	0.943	84	0.935
25	0.802	25	0.802	55	0.897	85	0.882
26	0.881	26	0.881	56	0.949	86	0.933
27	0.98	27	0.98	57	1	87	0.989
28	0.746	28	0.746	58	0.866	88	0.851
29	0.819	29	0.819	59	0.907	89	0.891
30	0.907	30	0.907	60	0.96	90	0.944

From the other equity perspectives of the population quantified by Gini AD and Gini TN, it is evident that the TE of the DMUs increases. This change is more significant from the AD perspective in DMUs (31–60). DMUs such as 31, 32, 33, 34, 35, and 36 with TE of 1 have less extensive base rail network inputs and incur low costs than the other new proposed rail networks. DMUs such as 39,45,51,57 also have the highest TE score of "1″ as they incorporate the proposed diverse rail network and integrated bus network, resulting in higher outputs with some input increase. In the case of the vertical equity perspective defined by TN, although the DMUs with maximum TE remain the same, there is an increase in the efficiency score of the other DMUs. The output-oriented DEA tends to maximize both outputs, assigning higher efficiency for collective performance given the inputs. For the mentioned cases, either the inputs are low for better outputs, or the outputs are high for higher inputs compared to the rest of the DMUs. Comparing the single outputs of either GINI or SCA, it can be noticed that there are other DMUs with better GINI or SCA, but the inputs for these DMUs are higher, making them less efficient. The most technically efficient DMUs based on different PuT networks are those centered on AD, meaning that the designed PuT system performs better when focused on the population demand with a propensity or need to use PuT than the PD and TN. This results from a tradeoff between the design of the PuT network in terms of new stations' locations, the length of the network, and sufficient PuT services in areas with demand and needs and its performance where the system attempts to maximize the equity and coverage goals. Achieving the maximum equity goals in serving the populations' needs would require a much denser network as in some DMUs, such as

16,17,25,26,28. Thus, these efficient designs provide a balance between the horizontal and vertical equity objectives.

As we generated the integrated bus and rail PuT networks using the five rail networks, the length of the rail network and frequencies needed at the train or metro stops are similar in most cases. The difference comes with the design of bus networks, which were designed based on different parameters, such as the minimum population in the area to locate a stop and the minimum and maximum distance between stops, which generate different bus network structures. The different constraints generated a different distribution of stops in the regions, providing different coverage and outputs. Although DMUs 1–30, 31–60, and 61–90 have similar inputs, they have different outputs from the equity perspectives with varying efficiency scores as they perform differently at different frontiers. DMU 1 (with outputs 63.03 and 0.1962) has a lower efficiency score than DMU 31 (with outputs 78.37 and 0.1962), showing that DMU 1 is not using its inputs as effectively as DMU 31. Similarly, the DMU pairs such as 27&61, 2&86, and 30&59 have the same efficiency score (0.98, 0.933, and 0.907) but different outputs and inputs, indicating that although their relative TE is the same, the absolute performance in input–output transformation varies. In the case of single-output and two-output DEA, the TE scores of DMUs 2, 27, and 30 remain the same, but the TE of DMUs 59, 61, and 86 improved in different perspectives. This suggests that even if DMUs are equally efficient (relative to the frontier), they operate at different scales in terms of the network structure or different environments characterized by equity-based population perspectives.

5. Discussion

This study sets out to address critical challenges in PTND by focusing on integrating equity and efficiency in creating multimodal transport systems. The integration of rail and bus networks, guided by a comprehensive approach to equity, seeks to ensure that PuT systems are operationally efficient and accessible to all populations. PuT system design should be based on the equity aspect and reaching the maximum population. It should not only serve the areas with maximum demand but also the needs of the population facing transport disadvantages due to their demographic background or socioeconomic conditions. Prioritizing areas with transport disadvantages and needs (vertical equity) along with potential demand (horizontal equity) requires targeted resource allocation to provide them with services for enhanced equity (Camporeale et al., 2019). In this context, the study first adopts an alternative approach to establish a balance between demand and needs given by the AD measure, obtained by adjusting the area's demand by a needs index. This helps achieve a tradeoff between the two commonly used horizontal and vertical equity perspectives and provides a third perspective of diagonal equity. We present a new methodology that combines the PTND and DEA approaches to first design multiple integrated rail and bus networks on a macroscopic census block level by incorporating PD, AD, and TN measures and then assess the efficiency of the proposed PTND scenarios in achieving the service coverage and equity goals. The efficiency of the system depends on the outputs achieved by a given set of inputs. Therefore, for the proposed designs, we determined network characteristics such as length, distribution of stops, and frequency. These inputs were used to determine the distribution of PuT services among the population and assess the equity and service coverage. For the 30 PTND scenarios, SCA values were calculated to evaluate the effectiveness of the proposed solution in covering the global population. Next, the equity assessment was made by calculating the GINI coefficient based on the three equity-based population perspectives: horizontal equity by PD, diagonal equity by AD, and vertical equity by TN. We generated a total of 90 DMUs from the 30 PuT design solutions with output based on the established perspectives of the population and evaluated the technical efficiency of all DMUs using DEA. Applying DEA as a tool to assess the performance of various network configurations has provided critical insights into how different design strategies impact efficiency and equity outcomes.

Methodological Innovations: The two-phase methodology developed in this study offers a new framework for PTND to introduce the horizontal, vertical, and diagonal equity perspectives in the early planning and design phase. For macroscale analysis, we provide a robust process for designing equitable and efficient transport networks by characterizing areas based on demand and needs and generating multiple network solutions that integrate rail and bus services in targeted areas. The use of DEA in this context helps identify the best-performing scenarios and highlights the trade-offs between different network configurations.

Equity as an output in DEA: Recent research has focused on considering accessibility (Ji et al., 2024; Martín et al., 2004) and passenger demand (Wang et al., 2022) as outputs in DEA to evaluate the effectiveness of the system in an equity context. This study uses the global equity measure as an output that considers walking access to PuT and service coverage across the population and allows for a better assessment of the system. The study's use of DEA to assess PuT networks' operational efficiency and equity in different contexts is a significant contribution. Unlike traditional methods such as AHP, MCDM, or CBA, DEA allows for the simultaneous evaluation of multiple inputs and outputs without requiring subjective judgments. This makes it particularly well-suited for complex, multi-criteria decision-making in PuT planning.

Integration of Equity and Efficiency: By focusing on the needs of disadvantaged populations and ensuring that transit services provide adequate coverage, the study contributes to a more inclusive transport planning process by targeting the PuT infrastructure interventions. This aligns with existing literature that underscores the importance of addressing spatial and social equity in transport planning (e.g., Karner, 2016; Wang et al., 2022). The proposed approach yields a more holistic view of PuT network performance as the results demonstrate that PTND focused on equity considerations, which improved both equity and efficiency. The AD measure provides a balance between horizontal and vertical equity when incorporated into the design, enhancing both efficiency and equity. This is in contrast to PD, which disregards the social needs of the population, and TN, which represents the needs of specific populations from the mobility survey. This was in line with the conclusion by (Bonner & Miller-Hooks, 2023) that the combined use of horizontal and vertical equity provided the best performance by covering the affluent population and accommodating the population with needs. In most cases, achieving equity involves trade-offs with network expansion or maximum efficiency. This aligns with Ji et al. (2024), who argue that the goal should be to enable most residents to benefit from PuT rather than striving for absolute equity and complete efficiency, which is nearly impossible to achieve.

The findings of this study have important implications for policymakers and urban planners. By adopting a methodology that integrates equity into the design process, transport authorities can create networks that better serve all population segments, particularly those typically underserved. Moreover, the application of DEA provides a rigorous, objective means of evaluating the efficiency of different network designs, which can help guide investments and optimize resource allocation. These results are crucial for strategic decision-making, allowing organizations to identify inefficient areas and develop plans to improve overall performance.

6. Conclusions and limitations

This study underscores the importance of integrating equity into PTND. By employing a comprehensive methodology, including DEA, we have demonstrated how different network configurations can be evaluated for both efficiency and equity. This paper focuses on two key objectives: (1) integrating equity based on defined measures into PTND to propose different designs, and (2) achieving a balance between efficiency and social equity. The goal is to create systems that are: i) equitable, ensuring equal opportunities for all urban residents and addressing the needs of specific societal groups; ii) accessible, providing convenient access to transit services within walking distance; and iii) demand-need sustainable, capturing the population demand with needs and encouraging a modal shift from private cars to public transit by making services more inclusive and practical.

By considering the social and physical structures of PTND, this approach aims to design transit networks that meet diverse needs while fostering greater equity and sustainability. The adopted methodology allows for proactive consideration of equity measures in the PTND process that serves as powerful decision support tools during the early planning and design phase. The results from the service coverage and achieved equity level through GINI highlight that prioritizing needs along with the potential demand provides to achieve the objectives of contrasting horizontal and vertical equity objectives. The higher efficiency scores of the proposed PuT networks also validated that the use of AD and TN measures representing diagonal and vertical equity can successfully fulfill the objective of balance between equity and efficiency. The insights from this research can help guide the development of more inclusive, efficient, and effective PuT systems, ultimately contributing to improved accessibility and quality of life for all urban residents.

While this study makes significant strides in advancing the PTND methodology, there are limitations that future research could address. For instance, the study focused on a more macroscopic purview of the PuT system design and evaluation in serving the areas to the population's demand and needs. Future research can adopt this approach to select efficient alternatives and optimize for a more detailed network with the on-road location of stops, frequency settings based on changing demand needs, timetable scheduling, and fleet management. Researchers could apply this methodology to different geographic contexts to explore the integration of other modes of transport, such as cycling or walking networks, into the overall PuT system. Additionally, while DEA is a powerful tool for efficiency analysis, its results are sensitive to the choice of inputs and outputs. Future studies could explore the use of alternative efficiency metrics or combine DEA with other decision-making tools to capture a broader range of performance indicators.

CRediT authorship contribution statement

Mudassar Shafiq: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marco Amorim:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis. **António Couto:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex A: Pseudo code of the algorithm to generate bus stations and lines

.

```
# Initialize parameters
Set KPI
Set max_stops
Set distance_interval
Set minimum_pop
# Create an empty DataFrame to store selected zones (df_selected)
df_selected = Empty DataFrame
# Track the current size of df_selected
current_size = length of df_selected
# Iterate over line numbers, starting from 1, until no new zones are selected
For each line number starting from 1:
# Call the function select_zones_v1_1 to select zones for the current line
df_selected = select_zones_v1_1(max_stops, KPI, df, minimum_pop, distance_interval, line_number, df_selected)
# Check if the size of df_selected has changed
If length of df_selected is equal to current_size:
Break the loop # No more zones were added
Else:
# Update current_size to the new size of df_selected
current_size = length of df_selected
```

Annex B: Pseudo code of the main function used in the bus stops generation algorithm

.

```
Function select_zones_v1_1(max_stops, KPI, df, minimum_pop, distance_interval, line_number, df_selected):
# Initialize variables
current_station = None
round_= "initial"
#First phase: if starting stations are available
# Step 1: Define starting station based on initial criteria
starting_station = filter df where:
```

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(*continued*)

– 'initial_station' == 1
– 'Population' > minimum_pop
– 'Distance' <= max distance in distance_interval
– 'nbr_BGRI11′ and 'src_BGRI11′ are not in df_selected
If starting_station is not empty:
 # Choose station with maximum KPI
current_station = **get** 'nbr_BGRI11′ of station with max KPI
Add selected station to df_selected
Assign line_number, Stop = 0, and Round = "initial" to selected station
 # Step 2: Find up to max_stops-1 additional stations
For each stop from 1 to max_stops-1:
next_station = filter df where:
– 'src_BGRI11′ == current_station
– 'nbr_BGRI11′ not in df_selected
forbidden_df = filter df where:
– 'nbr_BGRI11′ is in df_selected
– 'Distance' < min distance in distance_interval
next_station = **exclude** stations in forbidden_df from next_station
If next_station is not empty:
next_station = **filter** where:
– 'Population_nbr' > minimum_pop
– 'Distance' within distance_interval
If next_station is not empty:
current_station = **get** 'nbr_BGRI11′ of station with max KPI
Add selected station to df_selected
Assign line_number, Stop = current stop number, and Round = "initial"
Else:
Break loop *# No more stations meet criteria*
Else:
Break loop *# No more stations for current station*
Else:
round_= "extra"
#Second phase: if starting stations are not available
 # Step 1: Find alternative starting station
starting_station = filter df where:
– 'Population' > minimum_pop
– 'Distance' <= max distance in distance_interval
– 'nbr_BGRI11′ and 'src_BGRI11′ are not in df_selected
If starting_station is not empty:
 # Same selection process as before
current_station = **get** 'nbr_BGRI11′ of station with max KPI
Add selected station to df_selected
Assign line_number, Stop = 0, and Round = "extra"
 # Step 2: Find up to max_stops-1 additional stations
For each stop from 1 to max_stops-1:
next_station = **filter** df where:
– 'src_BGRI11′ == current_station
– 'nbr_BGRI11′ not in df_selected
forbidden_df = **filter** df where:
– 'nbr_BGRI11′ is in df_selected
– 'Distance' < min distance in distance_interval
next_station = exclude stations in forbidden_df from next_station
If next_station is not empty:
next_station = **filter** where:
– 'Population_nbr' > minimum_pop
– 'Distance' within distance_interval
If next_station is not empty:
current_station = get 'nbr_BGRI11′ of station with max KPI
Add selected station to df_selected
Assign line_number, Stop = current stop number, and Round = "extra"
Else:
Break loop *# No more stations meet criteria*
Else:
Break loop *# No more stations for current station*
 # Reset index of df_selected and return it
Reset index of df_selected
Return df_selected

Annex C: Bus network characteristics integrated with the base and proposed rail networks

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Rail network	Rail + Bus PuT network	Bus stop distance interval (meters)	Minimum population in subsection	Number of bus lines	Length of bus lines	Number of urban bus stops	Number of Suburban bus stops
Base Case	Scenario 1	500 < SD < 2000	10	919	5114.92	2883	4254
	Scenario 2	500 < SD < 2000	15	869	4810.96	2747	3918
	Scenario 3	500 < SD < 2000	20	819	4435.84	2651	3500
	Scenario 4	500 < SD < 5000	10	938	5953.57	2992	4507
	Scenario 5	500 < SD < 5000	15	884	5545.32	2902	4130
	Scenario 6	500 < SD < 5000	20	842	5072.88	2802	3674
Proposed Rail Network 2	Scenario 7	500 < SD < 2000	10	1068	5160.45	3029	4333
	Scenario 8	500 < SD < 2000	15	1023	7739.66	2906	4016
	Scenario 9	500 < SD < 2000	20	973	4487.10	2814	3600
	Scenario 10	500 < SD < 5000	10	1082	5965.80	3147	4592
	Scenario 11	500 < SD < 5000	15	1031	5627.58	3060	4231
	Scenario 12	500 < SD < 5000	20	987	5165.38	2958	3778
Proposed Rail Network 3	Scenario 13	500 < SD < 2000	10	1067	5230.81	3062	4378
	Scenario 14	500 < SD < 2000	15	1023	4885.04	2945	4009
	Scenario 15	500 < SD < 2000	20	968	4501.42	2845	3581
	Scenario 16	500 < SD < 5000	10	1089	6049.12	3174	4646
	Scenario 17	500 < SD < 5000	15	1037	5640.31	3067	4245
	Scenario 18	500 < SD < 5000	20	988	5161.86	2964	3783
Proposed Rail Network 4	Scenario 19	500 < SD < 2000	10	1068	5180	3048	4338
	Scenario 20	500 < SD < 2000	15	1020	4867.98	2901	4034
	Scenario 21	500 < SD < 2000	20	975	4497.27	2816	3607
	Scenario 22	500 < SD < 5000	10	1074	6001.08	3163	4573
	Scenario 23	500 < SD < 5000	15	1026	5649	3055	4240
	Scenario 24	500 < SD < 5000	20	985	5177.70	2970	3766
Proposed Rail Network 5	Scenario 25	500 < SD < 2000	10	1140	8507.46	3171	4445
	Scenario 26	500 < SD < 2000	15	1082	4973.59	3020	4114
	Scenario 27	500 < SD < 2000	20	1025	7219.82	2916	3678
	Scenario 28	500 < SD < 5000	10	1152	6103.83	3267	4698
	Scenario 29	500 < SD < 5000	15	1095	5737.21	3162	4347
	Scenario 30	500 < SD < 5000	20	1044	5259.39	3056	3873

Annex D: Single output-oriented DEA results

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DMUs	TE	Output	Inputs					
		SCA	Metro lines (km)	Raillines(km)	Buslines(km)	Metrostops*Freq	Railstops*Freq	Busstops*Freq
1	0.876	14.32	74.70	152.10	5114.92	190,935	38,228	5,010,000
2	0.933	14.26	74.70	152.10	4810.96	190,935	38,228	4,706,000
3	1	14.13	74.70	152.10	4435.84	190,935	38,228	4,401,000
4	0.842	14.44	74.70	152.10	5953.57	190,935	38,228	5,245,500
5	0.887	14.29	74.70	152.10	5545.32	190,935	38,228	4,967,000
6	0.954	14.18	74.70	152.10	5072.88	190,935	38,228	4,639,000
7	0.868	19.33	130.81	216.33	5160.45	330,347	51,128	5,195,500
8	0.919	19.12	130.81	216.33	7739.66	330,347	51,128	4,914,000
9	1	19.15	130.81	216.33	4487.10	330,347	51,128	4,614,000
10	0.826	19.44	130.81	216.33	5965.80	330,347	51,128	5,443,000
11	0.881	19.42	130.81	216.33	5627.58	330,347	51,128	5,175,500
12	0.946	19.13	130.81	216.33	5165.38	330,347	51,128	4,847,000
13	0.803	17.61	112.16	253.75	5230.81	272,347	69,928	5,251,000
14	0.885	17.54	112.16	253.75	4885.04	272,347	69,928	4,949,500
15	0.984	17.30	112.16	253.75	4501.42	272,347	69,928	4,635,500
16	0.748	17.69	112.16	253.75	6049.12	272,347	69,928	5,497,000
17	0.825	17.66	112.16	253.75	5640.31	272,347	69,928	5,189,500
18	0.923	17.56	112.16	253.75	5161.86	272,347	69,928	4,855,500
19	0.821	18.04	115.53	284.08	5180.00	282,347	65,878	5,217,000
20	0.901	17.99	115.53	284.08	4867.98	282,347	65,878	4,918,000
21	1	17.88	115.53	284.08	4497.27	282,347	65,878	4,619,500
22	0.768	18.13	115.53	284.08	6001.08	282,347	65,878	5,449,500
23	0.831	17.95	115.53	284.08	5649.00	282,347	65,878	5,175,000
24	0.935	18.00	115.53	284.08	5177.70	282,347	65,878	4,853,000
25	0.801	19.11	147.25	285.74	8507.46	303,612	71,578	5,393,500
26	0.881	19.04	147.25	285.74	4973.59	303,612	71,578	5,077,000
27	0.98	18.92	147.25	285.74	7219.82	303,612	71,578	4,755,000
28	0.746	19.03	147.25	285.74	6103.83	303,612	71,578	5,616,000
29	0.819	19.13	147.25	285.74	5737.21	303,612	71,578	5,335,500
30	0.907	18.87	147.25	285.74	5259.39	303,612	71,578	4,992,500

Annex E: Two outputs-oriented DEA results

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DMUs	TE	Outputs		DMUs	TE	Outputs		DMUs	TE	Outputs		Inputs					
		Inverse GiniPD	SCA			Inverse GiniAD	SCA			Inverse GiniTN	SCA	Metro lines (km)	Raillines(km)	Buslines(km)	Metrostops*Freq	Railstops*Freq	Busstops*Freq
1	0.877	63.03	0.1962	**31**	**1**	**78.37**	**0.1962**	61	0.98	76.65	0.1962	**74.70**	**152.10**	**5114.92**	**190,935**	**38,228**	**5,010,000**
2	0.933	62.12	0.2089	**32**	**1**	**77.51**	**0.2089**	62	0.98	75.78	0.2089	**74.70**	**152.10**	**4810.96**	**190,935**	**38,228**	**4,706,000**
3	**1**	**60.77**	**0.2239**	**33**	**1**	**76.27**	**0.2239**	**63**	**1**	**74.54**	**0.2239**	**74.70**	**152.10**	**4435.84**	**190,935**	**38,228**	**4,401,000**
4	0.842	64.25	0.1885	**34**	**1**	**79.63**	**0.1885**	64	0.981	77.86	0.1885	**74.70**	**152.10**	**5953.57**	**190,935**	**38,228**	**5,245,500**
5	0.887	63.43	0.1987	**35**	**1**	**78.89**	**0.1987**	65	0.981	77.10	0.1987	**74.70**	**152.10**	**5545.32**	**190,935**	**38,228**	**4,967,000**
6	0.955	62.08	0.2137	**36**	**1**	**77.69**	**0.2137**	66	0.983	75.90	0.2137	**74.70**	**152.10**	**5072.88**	**190,935**	**38,228**	**4,639,000**
7	0.868	63.75	0.2547	**37**	**0.896**	**80.12**	**0.2547**	67	0.883	78.92	0.2547	130.81	216.33	5160.45	330,347	51,128	5,195,500
8	0.919	63.06	0.2675	38	0.943	79.47	0.2675	68	0.93	78.25	0.2675	130.81	216.33	7739.66	330,347	51,128	4,914,000
9	**1**	**61.99**	**0.2884**	**39**	**1**	**78.42**	**0.2884**	**69**	**1**	**77.21**	**0.2884**	**130.81**	**216.33**	**4487.10**	**330,347**	**51,128**	**4,614,000**
10	0.826	64.60	0.2441	40	0.859	80.92	0.2441	70	0.847	79.71	0.2441	130.81	216.33	5965.80	330,347	51,128	5,443,000
11	0.881	64.02	0.2583	**41**	0.902	**80.35**	0.2583	71	0.89	79.15	0.2583	**130.81**	**216.33**	**5627.58**	**330,347**	**51,128**	**5,175,500**
12	0.946	62.85	0.2747	42	0.956	79.24	0.2747	72	0.946	78.05	0.2747	130.81	216.33	5165.38	330,347	51,128	4,847,000
13	0.804	65.20	0.2294	43	0.9	81.79	0.2294	73	0.88	80.04	0.2294	112.16	253.75	5230.81	272,347	69,928	5,251,000
14	0.885	64.42	0.2440	44	0.947	81.07	0.2440	74	0.926	79.31	0.2440	112.16	253.75	4885.04	272,347	69,928	4,949,500
15	0.984	63.41	0.2597	**45**	**1**	**80.08**	**0.2597**	75	0.991	78.33	0.2597	**112.16**	**253.75**	**4501.42**	**272,347**	**69,928**	**4,635,500**
16	0.748	66.03	0.2196	46	0.867	82.55	0.2196	76	0.848	80.79	0.2196	112.16	253.75	6049.12	272,347	69,928	5,497,000
17	0.825	65.41	0.2339	47	0.912	82.00	0.2339	77	0.892	80.23	0.2339	112.16	253.75	5640.31	272,347	69,928	5,189,500
18	0.923	64.26	0.2514	48	0.962	80.85	0.2514	78	0.942	79.09	0.2514	112.16	253.75	5161.86	272,347	69,928	4,855,500
19	0.821	63.56	0.2369	49	0.883	79.72	0.2369	79	0.869	78.51	0.2369	115.53	284.08	5180.00	282,347	65,878	5,217,000
20	0.901	62.97	0.2511	50	0.931	79.19	0.2511	80	0.918	77.98	0.2511	115.53	284.08	4867.98	282,347	65,878	4,918,000
21	**1**	**61.86**	**0.2688**	**51**	**1**	**78.12**	**0.2688**	**81**	**1**	**76.90**	**0.2688**	**115.53**	**284.08**	**4497.27**	**282,347**	**65,878**	**4,619,500**
22	0.769	64.37	0.2276	52	0.852	80.45	0.2276	82	0.839	79.24	0.2276	115.53	284.08	6001.08	282,347	65,878	5,449,500
23	0.831	63.79	0.2385	53	0.891	79.90	0.2385	83	0.877	78.67	0.2385	115.53	284.08	5649.00	282,347	65,878	5,175,000
24	0.935	62.64	0.2584	54	0.943	78.81	0.2584	84	0.935	77.59	0.2584	115.53	284.08	5177.70	282,347	65,878	4,853,000
25	0.802	66.26	0.2429	55	0.897	83.86	0.2429	85	0.882	82.41	0.2429	147.25	285.74	8507.46	303,612	71,578	5,393,500
26	0.881	65.62	0.2578	56	0.949	83.32	0.2578	86	0.933	81.86	0.2578	147.25	285.74	4973.59	303,612	71,578	5,077,000
27	0.98	64.63	0.2764	**57**	**1**	**82.38**	**0.2764**	**87**	**0.989**	**80.92**	**0.2764**	**147.25**	**285.74**	**7219.82**	**303,612**	**71,578**	**4,755,000**
28	0.746	66.80	0.2316	58	0.866	84.30	0.2316	88	0.851	82.84	0.2316	147.25	285.74	6103.83	303,612	71,578	5,616,000
29	0.819	66.24	0.2466	59	0.907	83.84	0.2466	89	0.891	82.37	0.2466	147.25	285.74	5737.21	303,612	71,578	5,335,500
30	0.907	65.21	0.2628	60	0.96	82.95	0.2628	90	0.944	81.48	0.2628	147.25	285.74	5259.39	303,612	71,578	4,992,500

Data availability

Data will be made available on request.

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