

Data-driven policy-making for equity-aware shared mobility: building the case study of Porto

Diogo Carvalho Viana

Dissertação de Mestrado

Supervisor at FEUP: Maria Beatriz Brito Oliveira

Co-supervisor at FEUP: Maria João Martins dos Santos

Co-supervisor at FEUP: Telmo Manuel Sampaio Pinto de Matos



FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Master in Industrial Engineering and Management

2026-06-25

Resumo

Políticas públicas baseadas em dados para uma mobilidade partilhada orientada pela equidade: aplicação ao caso de estudo do Porto

A mobilidade urbana enfrenta atualmente grandes desafios relacionados com as transições digital, ambiental e energética, bem como com a necessidade de garantir sistemas de transporte mais acessíveis, inclusivos e sustentáveis. Neste contexto, os serviços de mobilidade partilhada têm vindo a ser cada vez mais discutidos como potenciais complementos ao transporte público convencional, particularmente enquanto soluções de primeira e última milha. No entanto, os seus benefícios não são automáticos: se forem mal planeados, estes serviços podem reforçar desigualdades no acesso à mobilidade e competir com o transporte público convencional em vez de o complementar.

O principal objetivo desta dissertação é desenvolver uma metodologia de apoio à decisão para a localização de serviços de mobilidade partilhada, com vista à melhoria da acessibilidade urbana a partir de uma perspetiva de equidade vertical, isto é, centrada na inclusão social e na priorização da melhoria da acessibilidade para indivíduos desfavorecidos que enfrentam maior vulnerabilidade relacionada com a mobilidade. Para esse efeito, é proposto um framework baseado em dados que combina a análise da acessibilidade fornecida pelo atual sistema de transportes, indicadores socioeconómicos e demográficos, Sistemas de Informação Geográfica (SIG) e *heatmaps* para identificar áreas prioritárias de intervenção.

O framework metodológico proposto está estruturado em quatro etapas principais: em primeiro lugar, a recolha e preparação de dados geoespaciais, de transporte, demográficos e socioeconómicos; em segundo lugar, a caracterização da rede atual de transporte público, definida como o cenário As-Is; em terceiro lugar, a identificação de áreas prioritárias de intervenção através de *heatmaps* baseados em SIG; e, por fim, a simulação e avaliação do impacto de cenários alternativos de política pública para a mobilidade partilhada, comparando os respetivos ganhos de acessibilidade, a distribuição espacial dos benefícios, a orientação para a equidade e o esforço de investimento. A metodologia é aplicada ao caso de estudo da cidade do Porto, avaliando o potencial de implementação de hubs de carsharing elétrico como solução complementar de primeira e última milha ao sistema de transporte público existente.

A principal contribuição desta dissertação consiste no desenvolvimento de uma ferramenta de apoio à decisão que permite comparar cenários alternativos de política pública de forma visual, interpretável e sensível à equidade. Em vez de propor uma única solução ótima, a metodologia torna explícitos os trade-offs associados a diferentes estratégias de implementação, apoiando decisores políticos e autoridades de transporte na integração mais informada e equitativa de serviços de mobilidade partilhada nas redes urbanas de transporte.

Abstract

Urban mobility is currently facing major challenges related to digital, environmental, and energy transitions, as well as the need to ensure more accessible, inclusive, and sustainable transport systems. In this context, shared mobility services have been increasingly discussed as potential complements to conventional public transport, particularly as first- and last-mile solutions. However, their benefits are not automatic: if poorly planned, these services may reinforce inequalities in access to mobility, and compete with conventional public transport rather than complement it.

The main objective of this dissertation is to develop a decision-support methodology for locating shared mobility services to improve urban accessibility from a vertical equity perspective, that is, focusing on social inclusion and prioritizing the improvement of accessibility for disadvantaged individuals facing greater mobility-related vulnerability. To this end, a data-driven framework is proposed that combines an analysis of the accessibility provided by the current transport system, socioeconomic and demographic indicators, Geographic Information Systems (GIS), and heatmaps to identify priority areas for intervention.

The proposed methodological framework is structured into four main stages: first, the collection and preparation of geospatial, transport, demographic, and socioeconomic data; second, the characterization of the current public transport network, defined as the As-Is scenario; third, the identification of priority intervention areas through GIS-based heatmaps; and fourth, the simulation and impact assessment of alternative shared mobility policy scenarios, comparing their accessibility gains, spatial distribution of benefits, equity orientation, and investment effort. The methodology is applied to the case study of the city of Porto, assessing the potential implementation of electric carsharing hubs as a complementary first- and last-mile solution to the existing public transport network.

The main contribution of this dissertation is the development of a decision-support tool that enables the comparison of alternative public policy scenarios in a visual, interpretable, and equity-sensitive way. Rather than proposing a single optimal solution, the methodology makes explicit the trade-offs associated with different implementation strategies, supporting policy-makers and transport authorities in the more informed and equitable integration of shared mobility services into urban transport networks.

Acknowledgements

First of all, I would like to thank my supervisors, Beatriz Oliveira, Maria Santos and Telmo Matos, for the opportunity to carry out this work, for their trust, constant attention, and for the many hours of meetings, always guided by constructive and thoughtful comments. This meant a lot to me.

To my family and friends, thank you for all your patience and support over these past few months, and always. To Maria João, a special thank you for always being there, both in the best moments and in the most difficult ones.

Diogo Viana

Contents

1	Introduction	1
2	Literature review	3
2.1	Accessibility and equity	3
2.1.1	Accessibility in urban mobility	3
2.1.2	Equity-aware policy-making	4
2.1.3	Accessibility measures	7
2.1.4	Equity indicators	8
2.2	Shared mobility	10
2.2.1	Concept and typologies	11
2.2.2	Impact and challenges	13
2.3	Data-driven policy-making	16
2.3.1	Policy concept	18
2.3.2	The role of policy-making in the shared mobility context	19
2.3.3	How to evaluate policy outcomes: Cost-Benefit Analysis vs Multi-Criteria Analysis	22
3	Framework for designing equity-aware shared mobility policies	23
3.1	Conceptual framework	24
3.2	Data-driven framework for locating shared mobility services	25
4	Case study: policy-support tool for Porto	29
4.1	Context and motivation	29
4.2	Data collection and preparation	30
4.3	Characterization of the current transport network: As-Is	33
4.4	Accessibility landscape and shared mobility scenarios: To-Be	37
4.4.1	Building the heatmaps	37
4.4.2	Shared mobility scenarios: To-Be	45
4.5	Impact assessment	49
5	Conclusion	59
	References	63
A	Sensitivity analysis results	69
B	Sustainable Development Goals (SDG)	75

Acronyms and Symbols

B2C	Business-to-Consumer
CBA	Cost-Benefit Analysis
GIS	Geographic Information Systems
GTFS	General Transit Feed Specification
HOV	High-Occupancy Vehicle
INE	Instituto Nacional de Estatística
IoT	Internet of Things
MaaS	Mobility as a Service
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
P2P	Peer-to-Peer
SAVs	Shared Autonomous Vehicles
SDG	Sustainable Development Goal(s)
SIG	Sistemas de Informação Geográfica
SRAIs	Socially Relevant Accessibility Impacts
STEPS	Spatial, Temporal, Economic, Physiological, and Social

List of Figures

2.1	Relationships between components of accessibility by Geurs and van Wee (2004)	5
2.2	The Lorenz curve and Gini coefficient (Karner et al., 2025)	9
2.3	Shared mobility types (Guan et al., 2025)	12
2.4	General framework of sustainable shared mobility systems by Zhu et al. (2023)	19
2.5	The framework of forms of incentives by Guan et al. (2025)	20
3.1	Data-driven policy-making for equity-aware shared mobility: a framework	26
3.2	Summary of the proposed methodological framework	27
4.1	The 243 statistical sections composing the city of Porto	31
4.2	Porto bus and metropolitan transport network	32
4.3	Lorenz curve of the distribution of the calculated accessibility among the population of Porto	35
4.4	Accessibility heatmap	38
4.5	Accessibility heatmap and its relation with the metro line	39
4.6	Example of the 800-meter centroid buffer used to capture nearby public transport stops. Centroid in yellow, transport stops in orange.	40
4.7	Alternative 2: priority = $0.3A + 0.5PTF + 0.1IV + 0.1CAV$	44
4.8	Priority heatmap	45
4.9	Scenario 1	46
4.10	Scenario 2	47
4.11	Scenario 3	48
4.12	Scenario 4	49
4.13	Accessibility improvement in scenario 1	50
4.14	Accessibility improvement in scenario 2	51
4.15	Accessibility improvement in scenario 3	52
4.16	Accessibility improvement in scenario 4	52
4.17	Distribution of travel times to the nearest major public transport node under the As-Is situation and alternative policy scenarios	53
4.18	Accessibility distribution analysis sorted by priority	55
4.19	Accessibility distribution analysis sorted by accessibility	56
4.20	Trade-off between accessibility and investment for a relative cost difference between private and public station locations of 1:3	57
4.21	Trade-off between accessibility and investment for a relative cost difference between private and public station locations of 1:5	58
A.1	Alternative 3: priority = $0.3A + 0.1PTF + 0.5IV + 0.1CAV$	69
A.2	Alternative 4: priority = $0.3A + 0.1PTF + 0.1IV + 0.5CAV$	70
A.3	Alternative 5: priority = $0.3A + 0.2PTF + 0.4IV + 0.1CAV$	70

A.4	Alternative 6: $\text{priority} = 0.3A + 0.2\text{PTF} + 0.1\text{IV} + 0.4\text{CAV}$	70
A.5	Alternative 7: $\text{priority} = 0.3A + 0.4\text{PTF} + 0.15\text{IV} + 0.15\text{CAV}$	71
A.6	Alternative 8: $\text{priority} = 0.3A + 0.1\text{PTF} + 0.3\text{IV} + 0.3\text{CAV}$	71
A.7	Alternative 9: $\text{priority} = 0.3A + 0.1\text{PTF} + 0.4\text{IV} + 0.2\text{CAV}$	71
A.8	Alternative 10: $\text{priority} = 0.3A + 0.1\text{PTF} + 0.2\text{IV} + 0.4\text{CAV}$	72
A.9	Alternative 11: $\text{priority} = 0.4A + 0.25\text{PTF} + 0.2\text{IV} + 0.15\text{CAV}$	72
A.10	Alternative 12: $\text{priority} = 0.5A + 0.2\text{PTF} + 0.15\text{IV} + 0.15\text{CAV}$	72
A.11	Alternative 13: $\text{priority} = 0.6A + 0.15\text{PTF} + 0.15\text{IV} + 0.1\text{CAV}$	73
A.12	Alternative 14: $\text{priority} = 0.7A + 0.1\text{PTF} + 0.1\text{IV} + 0.1\text{CAV}$	73

List of Tables

2.1	STEPS to transportation equity by Shaheen et al. (2017)	17
2.2	Howlett and Cashore Policy Taxonomy by Marsden and Reardon (2017) adapted from Howlett and Cashore (2009)	18
4.1	Sample size, average household income and car availability by IMob mobility zone	41
4.2	Weighting schemes tested in the sensitivity analysis	42
4.3	Summary statistics of ranking differences for the top 10% priority sections	43
4.4	Summary statistics of ranking differences for the top 10% priority sections under increased accessibility weights	44
B.1	SDGs, goals, contributions and performance indicators	76

Chapter 1

Introduction

Urban mobility is currently at the center of several simultaneous transformations. Digitalization, environmental concerns, and the energy transition are reshaping the way cities plan, operate, and regulate their transport systems (Secretaria-Geral do Ambiente, 2025). At the same time, population growth, urban expansion, and changing travel patterns are increasing pressure on conventional public transport networks, which remain essential for ensuring access to employment, services, and daily activities (Zhu et al., 2023).

The effective functioning of societies depends on people's ability to reach destinations via different modes of transport. In this context, promoting adequate levels of accessibility is a central goal of transport policy, while its ongoing improvement remains a key priority in the planning and development of transport systems (van Wee, 2016; Lucas et al., 2016). However, when policies aimed at enhancing mobility are designed and implemented, policy-makers and transport authorities must consider not only their overall benefits, but also how these benefits are distributed across territories and population groups. These distributional effects bring the concept of equity to the forefront of transport policy evaluation. Accessibility and equity in urban mobility are, therefore, interrelated concepts and constitute central concerns in transport planning and decision-making. Nevertheless, both concepts are characterized by multiple definitions, interpretations, and methodological approaches within the urban mobility literature. The same applies to the measures used to operationalize accessibility and equity, quantify accessibility levels, and assess their distributional outcomes. A literature review on these themes is therefore presented to clarify their conceptual foundations, examine how they have been measured in previous studies, and support the evaluation of transport policies and projects.

Shared mobility services have emerged as potential complements to conventional public transport systems. By providing flexible and on-demand mobility options, services such as carsharing, bikesharing, e-scooter sharing, and ridesharing may improve first- and last-mile connectivity, extend the reach of existing networks, and reduce dependence on private car use. However, these benefits are not automatic. The diffusion of shared mobility services also generates new operational and equity challenges. If poorly planned, these services may concentrate in central, high-demand, and more profitable areas, while leaving peripheral or socially vulnerable territories

underserved. Moreover, when shared mobility services are not properly integrated with the existing public transport network, they may compete with conventional public transport rather than complement it. This competitive relationship can undermine the efficiency of the overall mobility system and potentially contribute to additional transport-related externalities.

The main research problem addressed in this dissertation can therefore be formulated as follows: how can shared mobility services be planned, located, and integrated into the current transport network to support accessibility improvements from an equity perspective?

To address this question, the main objective of this dissertation is to develop a data-driven methodological framework to support policy-makers and transport authorities in locating shared mobility services from a vertical equity perspective. More specifically, this work combines accessibility analysis, equity-oriented criteria, and GIS-based spatial analysis to identify priority areas for intervention, simulate alternative policy scenarios, and assess their impacts. By doing so, it provides a tool that is visually intuitive, interpretable, and easy for decision-makers to communicate. The methodology is applied to the case study of the city of Porto (Portugal), focusing on carsharing hubs as a complementary first- and last-mile solution to improve access to major public transport nodes.

The dissertation is organized into four chapters. Chapter 1 introduces the research context, motivation, objectives, and structure of the dissertation. Chapter 2 presents the literature review. It discusses the accessibility and equity concepts in urban mobility, reviews various accessibility measures and equity indicators, examines the emergence, impacts, and challenges of shared mobility services, and explores the role of data-driven policy-making in transport planning. Chapter 3 synthesizes the lessons of the literature review into a conceptual framework and presents the proposed methodological framework of this thesis, bridging the lessons learned with the remainder of the dissertation work. Chapter 4 presents the application of the proposed framework to the case study of Porto. Chapter 5 presents the main conclusions of the dissertation. It summarises the contributions of the work, discusses its limitations, and identifies possible directions for future research.

Chapter 2

Literature review

The four sections of this chapter lay the foundation for this work through a literature review of the key themes addressed in this thesis. The first section (Section 2.1) discusses the concepts of accessibility and equity in urban mobility and how they have been measured in the literature. The second section (Section 2.2) explores the topic of shared mobility, including the definition, its typologies, and its potential impacts and challenges within the transport system. The third and final section (Section 2.3) goes along the topic of data-driven policy-making, providing a review of the literature on the concept of policy-making, its role in the context of shared mobility, and how to evaluate policy outcomes.

2.1 Accessibility and equity

To analyze the role of accessibility and equity in transport policy-making, it is first necessary to clarify what these concepts represent and how they are understood within the context of urban mobility. Equally important is understanding how these concepts can be operationalized and measured. The literature provides a wide range of definitions and methodological approaches for quantifying accessibility levels and evaluating how these levels are distributed across different social groups and geographical areas. Therefore, the objective of this section is to review these concepts and examine the main approaches used to measure accessibility and equity in urban mobility.

2.1.1 Accessibility in urban mobility

For societies to function effectively, individuals must have sufficient access to destinations through different transport modes. Ensuring an adequate level of accessibility constitutes a central objective of transport policy, and its continuous improvement remains a key priority in the transport system development (van Wee, 2016; Lucas et al., 2016).

Despite being a concept that spans multiple scientific fields, including transport planning, urban planning, and geography, accessibility is often misunderstood, poorly defined, and inadequately measured (Geurs and van Wee, 2004). As a result, both the definition and the measurement of accessibility in urban mobility have evolved over time and remain an active area of research (van

Wee, 2016). In his pioneering work on the impact of accessibility on land use, Hansen (1959) defined accessibility as "a measurement of the spatial distribution of activities about a point, adjusted for the ability and the desire of people or firms to overcome spatial separation". In Geurs and van Wee (2004), focusing specifically on passenger transport, accessibility is defined as "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)". To better conceptualize accessibility and support its measurement, these authors identify four key components that should ideally be considered when evaluating accessibility:

- **Land-use:** relates to the spatial distribution of opportunities across an area, such as the location and availability of jobs, services, retail facilities, and other activities. Accessibility is influenced by how these opportunities are geographically arranged and by the balance between their supply and the demand generated by the population.
- **Transportation:** refers to the characteristics and performance of the transport system that enable movement between origins and destinations. This includes factors such as travel time, monetary costs, reliability, comfort, and other aspects that determine the effort required to reach activities located in different areas.
- **Temporal:** accessibility is also shaped by time constraints. Opportunities may only be available at specific times of the day, and individuals have limited time available to travel and participate in activities. Therefore, the alignment between activity schedules, opening hours of services, and individuals' daily time budgets can significantly influence accessibility levels.
- **Individual:** concerns the characteristics of individuals and households that affect their ability to access opportunities. Factors such as income, age, physical ability, education, household responsibilities, and ownership of a private vehicle influence both the resources available for travel and the types of activities that individuals can realistically reach.

These four components interact with one another (see Figure 2.1), meaning that accessibility outcomes depend on the combined influence of land-use patterns, transport systems, temporal constraints, and individual characteristics.

2.1.2 Equity-aware policy-making

Transport policies and infrastructure projects often produce accessibility changes that are unevenly distributed across different population groups and geographical areas. For example, when a project reduces travel times or increases the number of accessible opportunities, the resulting benefits are rarely experienced equally; some households, income groups, or regions may benefit more than others. These distributional outcomes raise an important consideration in the evaluation of transport policies and projects: equity.

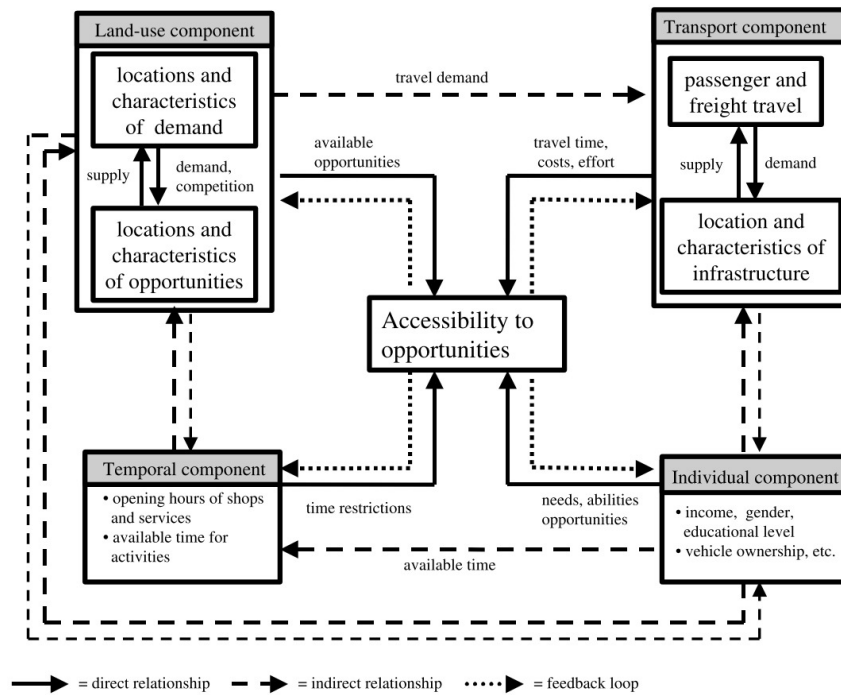


Figure 2.1: Relationships between components of accessibility by Geurs and van Wee (2004)

In simple terms, equity refers to the fairness with which impacts (benefits and costs) are distributed (Litman, 2025). However, as noted by van Wee and Mouter (2021), defining what is equitable (or not) can be quite complex, since it is an inherently normative and ethically contested concept. In other words, it is grounded in value judgments about what is considered fair, and different individuals or ethical frameworks may disagree on what a just distribution of costs and benefits should entail. Within the transport and accessibility literature, three ethical frameworks are commonly used to evaluate equity considerations in policy-making: utilitarianism, egalitarianism, and sufficientarianism (Thomopoulos et al., 2009; Wee et al., 2011; Lucas et al., 2016; Karner et al., 2025).

Utilitarianism holds that an action is morally justified if it maximizes overall societal welfare. In this perspective, an action is considered preferable when the total benefits for all individuals, after subtracting the costs, exceed those of any alternative (Thomopoulos et al., 2009). In most countries, cost-benefit analysis (CBA) is the primary method used to evaluate transport-related decision-making (Lucas et al., 2016). CBA is strongly rooted in utilitarian principles, as it assesses policies by aggregating their benefits and costs to determine whether they generate a net increase in societal welfare. This evaluation often relies on indicators such as net benefits and tends to emphasize operational efficiency and travel-time savings. However, CBA typically pays limited attention to how these benefits and costs are distributed among different social groups or regions. As a result, when policies aim explicitly to address inequalities in accessibility, relying solely on CBA may be problematic (Thomopoulos et al., 2009; Lucas et al., 2016; van Wee and Mouter, 2021).

Egalitarianism, in contrast, focuses on reducing inequalities rather than maximizing total welfare. Based on John Rawls' theory of justice, this perspective is grounded in the principle that individuals should be treated equally and that social arrangements should prioritize the well-being of the least advantaged members of society. Rawls argues that justice should emphasize the provision of certain fundamental goods, referred to as primary goods, for all individuals. Although Rawls did not explicitly identify transport accessibility as a primary social good, several authors have argued that accessibility to essential destinations can reasonably be interpreted as one (Wee et al., 2011; Martens et al., 2012; Lucas et al., 2016). From this perspective, evaluating transport policies involves prioritizing accessibility to key services – such as employment, food stores, and healthcare – and promoting a more balanced distribution of accessibility across social groups. (Wee et al., 2011; Lucas et al., 2016).

Sufficientarianism is grounded in the principle that all individuals should achieve an adequate level of well-being. This approach establishes a minimum threshold that should be considered sufficient to meet basic needs and sustain an acceptable quality of life (Lucas et al., 2016). Applied to accessibility, sufficientarianism suggests that all individuals should be guaranteed at least a basic level of access to essential services, such as food shops or healthcare facilities, within a reasonable travel time or distance. From this viewpoint, transport policies should aim to ensure that accessibility does not fall below this minimum standard. When individuals are unable to reach essential destinations within this threshold, they may be considered socially excluded (Lucas et al., 2016). Lucas et al. (2016) propose a quantitative method based upon the principles of egalitarianism and sufficientarianism to develop a measure of the "socially relevant accessibility impacts" (SRAIs) of transport policies, in response to the limitation of the CBA (utilitarianism) to assess the distribution effects of these policies.

Evaluating equity impacts in transportation planning can be challenging because multiple dimensions of equity and various types of impacts must be considered. Moreover, such analyses often require normative judgments in addition to simply describing distributional effects (Wee et al., 2011; Litman, 2025). Given the normative nature of the equity concept, it is important to first clarify which types of equity are discussed in the literature. Thomopoulos et al. (2009) identifies several categories of equity that may be relevant when evaluating transport-related policies and infrastructure projects. Among these, the following five are particularly relevant for analyzing the distribution of accessibility:

- **Horizontal equity:** emphasizes that individuals or groups with similar needs and abilities should be treated equally. In the context of transport accessibility, this implies that comparable individuals or regions should experience similar levels of accessibility and face similar costs (Litman, 2025).
- **Vertical equity:** focuses on social inclusion and emphasizes the need to prioritize disadvantaged individuals, groups, or regions. Policies guided by this principle aim to improve accessibility for populations that currently face lower levels of access to opportunities.

- **Egalitarian equity:** from an egalitarian perspective, policies should aim to reduce disparities in accessibility levels between individuals or groups, promoting a more balanced distribution of opportunities.
- **Spatial equity:** concerns the geographical distribution of the impacts of transport infrastructure and services. It focuses on how the location of individuals, communities, or regions influences their access to opportunities and how transport policies may reinforce or reduce these spatial inequalities.
- **Territorial equity:** often closely related to spatial equity, refers to fairness in the allocation of transport investments and services across geographical areas. This perspective emphasizes that regions should receive comparable levels of accessibility and transport service, with particular attention given to areas that are currently underserved.

Having analyzed the concepts of accessibility and equity within urban mobility, the following subsections review the main methods used in the literature to measure them.

2.1.3 Accessibility measures

A comprehensive review of accessibility measures is presented in Geurs and van Wee (2004), evaluating their suitability to assess land-use and transport strategies. In this paper, accessibility measures are analyzed according to several criteria, including their theoretical foundations, interpretability and communicability, data requirements, and applicability in social and economic evaluations. The authors further classify these measures into four main categories: infrastructure-based measures, location-based measures, person-based measures, and utility-based measures.

Infrastructure-based measures focus on the performance and service level of the transport system itself. Typical indicators include travel time, congestion levels, and average speeds on transport networks. These measures are relatively easy to operationalize and communicate, and the required data is often readily available.

Location-based measures analyse accessibility at locations. This category includes distance-based measures, contour measures, and potential accessibility measures (often referred to as gravity-based measures). Distance measures capture the connectivity between two locations using metrics such as travel time or distance. Contour measures count the number of opportunities that can be reached within a specified travel time, distance, or cost. Gravity-based measures extend this approach by weighting the sum of the opportunities in all destination zones according to travel costs using a distance-decay function, incorporating assumptions on a user's perceptions of transport. While this measure is widely used and relatively straightforward to compute, it may be less intuitive to interpret and communicate. Examples of works applying this type of measure can be seen in Alam et al. (2010), Järv et al. (2018), and Shafiq et al. (2024).

Person-based measures evaluate accessibility from the viewpoint of individuals, incorporating spatial and temporal constraints. They capture the set of activities an individual can realistically reach given personal time budgets, activity schedules, and mode-specific constraints. These measures can reflect detailed socio-demographic attributes (age, income, vehicle ownership) and therefore satisfy most theoretical criteria, but they require extensive individual-level data and are computationally intensive, limiting their practical application to small study areas.

Utility-based measures assess accessibility in terms of the utility or economic benefits that individuals derive from being able to access spatially distributed activities. The most common implementation is the log-sum (the denominator of a multinomial logit model), which aggregates the expected utility of all available travel-destination-mode alternatives into a single scalar. This measure can be linked to consumer surplus or compensation variation, allowing the monetary valuation of accessibility changes and facilitating economic cost-benefit analyses. While theoretically robust and suitable for economic evaluation, utility-based measures are complex and harder to interpret. Examples of works applying this type of measure can be seen in Niemeier (1997) and de Jong et al. (2007).

According to the authors, ideally, an accessibility measure should take into account all the components described in Subsection 2.1.1, although, in practice, this is not verified in most empirical studies, relying on a subgroup of these perspectives depending on the research objectives.

2.1.4 Equity indicators

When policy-makers aim to promote a more equitable distribution of accessibility, a key methodological decision concerns the selection of the indicator or set of indicators that are going to be used (Wee et al., 2011). These indicators capture how accessibility is distributed across different population groups and geographical areas, as well as how policies may alter this distribution. Various indicators for assessing equity are presented in the literature, with comprehensive explanations provided by Ramjerdi (2006), van Wee and Mouter (2021), and Karner et al. (2025). Among these, the most widely used indicators include the following:

The Lorenz Curve and the Gini Coefficient

The Lorenz Curve plots the cumulative distribution of a variable (e.g., income, accessibility, transport costs) along the y-axis against the cumulative share of the population ranked by that variable on the x-axis. A 45-degree line represents perfect equality; the actual curve typically lies below it, revealing inequality (see Figure 2.2). The Gini coefficient is calculated as the ratio of the area between the Lorenz curve and the equality line to the total area under the equality line, ranging from 0, perfect equality, to 1, perfect inequality (van Wee and Mouter, 2021; Karner et al., 2025).

In transport research, the Gini index is by far the most widely used metric for measuring distributional inequalities, with its popularity stemming from interpretability and ease of communication to policy-makers and the general public (van Wee and Mouter, 2021).

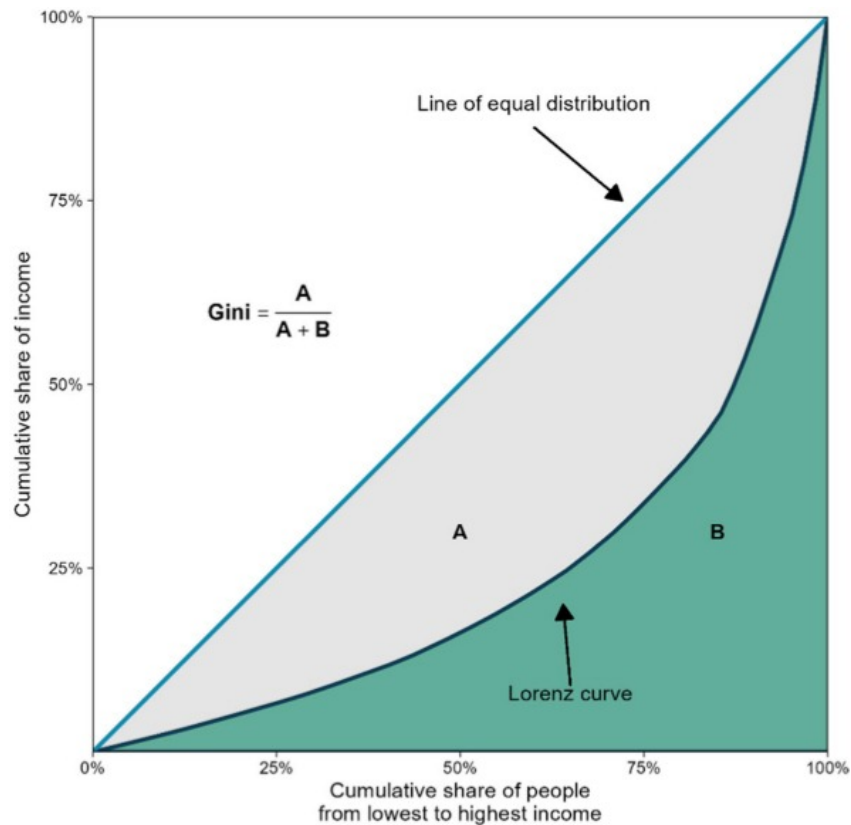


Figure 2.2: The Lorenz curve and Gini coefficient (Karner et al., 2025)

Several practical applications of the Gini coefficient can be found throughout the literature: Delbosc and Currie (2011) used it to assess the social exclusion effects of public transport services in Melbourne, Australia; Shafiq et al. (2024) evaluated the global inequity levels of the spatial distribution of the rail network in the metropolitan area of Porto; Pritchard et al. (2019) evaluated the spatial distribution of job accessibility, and the potential of the bicycle to reduce inequalities in the city of São Paulo, Brazil.

The Theil Index

The Theil index is calculated based on comparing the share of each unit (e.g., a region in a certain geographical area) in the total population for which the index is calculated, with the share of that unit in the output indicator (e.g., accessibility). In simple terms, it measures how much each unit's share of the outcome deviates from its expected share given its population size. Unlike the Gini coefficient, which captures overall inequality across all individuals/regions, the Theil index explicitly separates total inequality into two components: within-group inequality and between-group

inequality. The total Theil value corresponds to the sum of these two components, allowing researchers to identify which dimension contributes most to the observed inequalities. Higher values indicate greater levels of inequality. However, the Theil Index is more difficult to communicate to policy-makers and the public, reducing its practical utility compared to more intuitive measures (van Wee and Mouter, 2021; Karner et al., 2025).

In the transportation context, the Theil Index has been applied in several studies. For example, Jin et al. (2022) used it to examine the equity in accessibility to healthcare services, while Delafontaine et al. (2011) applied it to evaluate equity in accessibility to public service facilities through a case study of public libraries in Ghent, Belgium.

The Palma Ratio

The Palma ratio is an inequality indicator that compares the share of a variable (e.g., accessibility) held by the richest 10% of the population with the share held by the poorest 40%. Originally developed to measure income inequality, the index is based on the observation by Palma (2011) that the share of income received by the middle 40–90% of earners tends to remain relatively stable across countries and over time. One advantage of this measure is its simplicity and ease of interpretation, as it focuses on the extremes of the distribution that are often most relevant for policy discussions. However, the Palma ratio also has some limitations. In particular, it ignores middle-income groups and, because it relies on average values for each group, it does not capture inequality within those groups (van Wee and Mouter, 2021; Karner et al., 2025).

In the transport literature, the Palma ratio has been applied, for example, by Herszenhut et al. (2022) to assess the impact of transit monetary costs on transport inequality and Guzman and Oviedo (2018) to assess public transport subsidies in Bogotá.

Because no single indicator captures all dimensions of transport equity, and each indicator has its own characteristics and limitations – Gini captures total inequality irrespective of income distribution; Theil decomposes within- and between-group inequality; Palma focuses on extremes while ignoring the middle 40 percent – empirical evidence demonstrates that different indicators can lead to contradictory results (Karner et al., 2025). Therefore, van Wee and Mouter (2021) and Karner et al. (2025) highlight the importance of aligning the choice of the metric with the research's objective, comparing different equity measures, and making conscious methodological choices.

2.2 Shared mobility

In the words of the Portuguese Secretary of State for Mobility, "We are in the most demanding decade as far as mobility is concerned. It is currently at the epicenter of the confluence of three simultaneous transitions: the digital transition, the environmental transition, and the energy transition; all of which bring increasing challenges" (Expresso, 2026). Within this context, conventional public transport (e.g., metro, bus, train) continues to play a central role in urban mobility systems

by providing affordable and reliable access to employment, essential services, and daily activities (Tao et al., 2026). However, continued population growth, urban expansion, and evolving travel patterns are transforming the mobility needs in cities (Zhu et al., 2023). In response to these challenges, urban mobility systems are increasingly incorporating new transport services, particularly shared mobility solutions, such as shared micromobility (e.g., bicycles and e-scooters), ridesharing, ridesourcing, and carsharing (Tao et al., 2026). These services have experienced significant global growth in recent years (Sovacool et al., 2022; Coenegrachts et al., 2024).

Integration of these emerging services with conventional public transport has the potential to strengthen urban mobility systems by expanding travel options, enhancing flexibility, improving network connectivity, and promoting more accessible mobility. At the same time, the diffusion of these services also generates new operational and equity challenges (Shaheen et al., 2017; Tao et al., 2026).

A clear understanding of shared mobility, its operational characteristics, and its role within urban transport systems is important for the development of more sustainable mobility systems (Martinez et al., 2024). Accordingly, this section is structured as follows: Subsection 2.2.1 introduces the concept and typologies of shared mobility, while Subsection 2.2.2 examines its impacts and associated challenges, particularly in relation to the environment, the built environment, and, most importantly in the context of this thesis, urban mobility accessibility and equity.

2.2.1 Concept and typologies

Shared mobility is part of the broader and rapidly expanding phenomenon known as the sharing economy. First introduced by Felson and Spaeth (1978), the concept of the sharing economy focuses on optimizing underutilized resources to meet temporary user needs without requiring ownership, thereby improving asset utilization and promoting more sustainable consumption patterns (Guan et al., 2025).

Within this context, shared mobility systems enable multiple users to access the same physical mobility assets (e.g., bicycles, cars, or scooters) sequentially, typically on a pay-per-use basis. This contrasts with traditional ownership models, in which assets are purchased, maintained, and used exclusively by a single owner (Vine and Polak, 2015; Guan et al., 2025). The rapid growth of shared mobility has been strongly supported by technological advancements, including the widespread adoption of smartphones, the Internet of Things (IoT), advanced data analytics, and electronic payment systems. These technologies facilitate interactions between users and service providers, improve the matching of supply and demand, and enable the emergence of new business models based on on-demand service provision (Richter and Slowinski, 2019; Martinez et al., 2024).

Types of shared mobility

As a rapidly evolving field encompassing a wide range of mobility services and continuously developing business models, the terminology used to describe shared mobility modes in the existing

literature remains heterogeneous (Vine and Polak, 2015; Martinez et al., 2024; Guan et al., 2025). Shared mobility services vary significantly in their operational characteristics, including the type of vehicle (e.g., bicycles, cars, or scooters), the ownership structure of the fleet – such as peer-to-peer (P2P) models, in which individual vehicle owners provide access to their vehicles directly to other users, or business-to-consumer (B2C) models, where fleets are owned and operated by companies – and the access model, which may be based on free-floating or station-based systems.

Guan et al. (2025) presents a comprehensive review of the most commonly recognized types that can be categorized into three primary modes: vehicle sharing, trip sharing, and trip and delivery sharing (see Figure 2.3). In the context of this thesis, the two most relevant types of shared mobility are vehicle sharing and trip sharing, being those exclusively related to passenger trips.

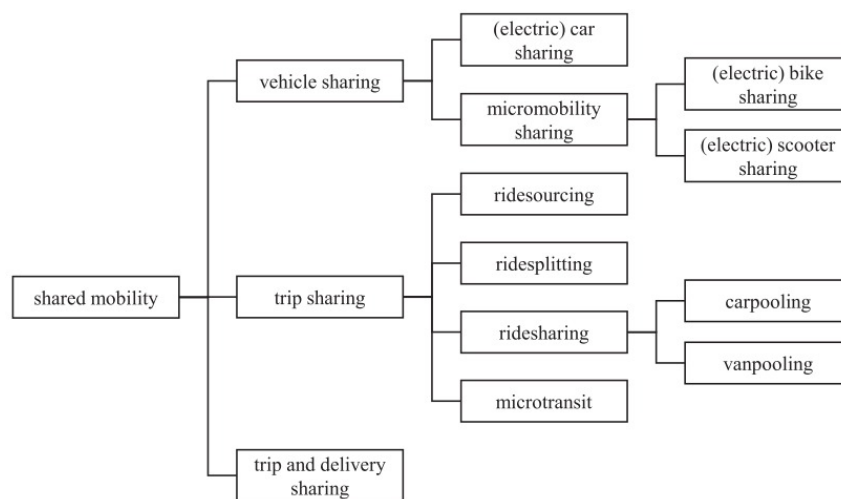


Figure 2.3: Shared mobility types (Guan et al., 2025)

Vehicle Sharing refers to mobility services that provide users with temporary access to private vehicles.

- **(Electric) carsharing** refers to mobility services that allow individuals to access a car temporarily without bearing the costs and responsibilities associated with ownership of the vehicle (Shaheen et al., 2015). Carsharing systems can be broadly classified into two main business models: business-to-consumer (B2C) and peer-to-peer (P2P) (Cohen and Kietzmann, 2014). In B2C carsharing, a company owns and operates the vehicle fleet, providing users with access to vehicles through either station-based systems or free-floating models. In contrast, P2P carsharing enables private vehicle owners to share their cars with others, typically through digital platforms that facilitate matching and transactions (Zhu et al., 2023).
- **Micromobility sharing** typically refers to lightweight vehicles designed for short-distance travel at relatively low speeds, including bicycles, e-bikes, e-scooters, and e-mopeds (Cohen and Kietzmann, 2014; Lazarus et al., 2020). These micromobility services have been widely

adopted around the world and are provided either in station-based or dockless models (Zhu et al., 2023).

Trip Sharing refers to mobility services in which multiple users share a vehicle for a given journey. These services can be broadly classified into four main categories: ridesourcing, ridesplitting, ridesharing, and microtransit.

- **Ridesourcing** (also mentioned as ride-hailing or e-hailing) connects passengers to nearby available drivers through an online platform. Well-known examples include services provided by companies such as Uber, Bolt, or Lyft (Wang and Yang, 2019; Guan et al., 2025).
- **Ridesplitting** (or ridepooling) is a pooled variant of ridesourcing, in which multiple passengers with similar itineraries share the same vehicle. These trips may involve intermediate stops or slight detours, with the travel cost divided among users (Wang et al., 2023; Guan et al., 2025).
- **Ridesharing**, in contrast, involves individuals, both drivers and passengers, who share a vehicle along a common route, typically to reduce travel costs such as fuel or parking fees (Furuhata et al., 2013). Ridesharing can be further divided into carpooling and vanpooling. Carpooling is an arrangement in which commuters share a car from a common origin, destination, or both. Vanpooling refers to commuters consisting of 7 to 15 people regularly commuting in vans or similar-sized vehicles (Zhu et al., 2023). The primary distinction between ridesplitting and ridesharing lies in the driver's travel requirements. In ridesplitting, mobility services are provided for earnings, whereas in ridesharing, drivers fulfill personal travel needs while reducing costs by taking passengers along (Guan et al., 2025).
- **Microtransit** consists of shuttle-based services with either fixed or flexible routes based on user demand (Zuniga-Garcia et al., 2022).

Although some studies classify ridesourcing as a form of trip sharing, this classification can be questioned within the context of transport planning and policy-making. Ridesourcing services often involve a single passenger (excluding the driver, who is providing a service in exchange for payment) and therefore do not necessarily constitute a shared trip.

Furthermore, it is important to note the rapid emergence of shared autonomous vehicles (SAVs). Although their widespread adoption remains limited – primarily due to safety and regulatory concerns – these systems have the potential to support multiple shared mobility services in the future, including carsharing and ridesharing (Zhu et al., 2023).

2.2.2 Impact and challenges

A comprehensive understanding of shared mobility impacts can help policy-makers maximize its benefits and mitigate its drawbacks, in order to achieve public policy objectives (Cohen and Shaheen, 2016). In this context, the literature highlights three key areas of impact: environmental

outcomes, effects on the built environment, and implications for accessibility and equity in urban mobility.

Environmental impact

The transport and mobility sector is one of the main sources of pollution in Portugal, accounting for approximately 30% of total greenhouse gas emissions and 35% of overall energy consumption, according to 2022 data (Secretaria-Geral do Ambiente, 2025). Therefore, it is imperative to develop and implement solutions to mitigate these externalities, to achieve the goals set by the European Green Deal, including a 55% reduction in emissions by 2030 (European Commission, 2019), a target that is also reflected in Portugal's 2030 National Energy and Climate Plan (Direção-Geral de Energia e Geologia, 2025).

Shared mobility is recognized for its potential to, in the right conditions, contribute to positive environmental outcomes and reduce transportation externalities. In the literature, this potential is attributed to several factors. First, shared mobility modes may reduce energy consumption by increasing vehicle occupancy, as in ridesharing, by promoting the use of hybrid, electric, or non-motorised vehicles, and by enabling more efficient vehicle use. For example, in carsharing systems, the same vehicle can serve multiple users and trips, reducing the need for several privately owned vehicles to perform similar journeys (Zhu et al., 2023). Second, lower energy consumption may contribute to reduced exhaust emissions, including CO₂ and other greenhouse gas emissions, thereby improving air quality (Zhu et al., 2023; Vélez, 2024). Third, shared mobility modes decrease the need for private vehicle ownership, helping solve one of the critical problems of modern societies, congestion, not only from reducing the need for private car ownership, but also through the improvement of space utilization in the car (e.g. ridesharing) and the use of non-motorized vehicles (e.g. shared micromobility), improving livability, reducing associated pollution (Zhu et al., 2023; Martinez et al., 2024), and noise pollution (Cohen and Shaheen, 2016).

However, the environmental impacts of shared mobility are challenging to draw directly, as different assessments on this matter show mixed results (Zhu et al., 2023; Vélez, 2024). Vélez (2024) provides a systematic literature review of studies that quantify the environmental impacts of different shared mobility modes, as well as the factors that influence these outcomes. These factors include service design and operational characteristics (e.g., fleet rebalancing strategies, which, to promote positive outcomes, may create trade-offs with provider profitability), modal shift due to shared mobility (i.e., whether shared mobility substitutes private car trips, competes with public transport, or replaces active modes such as walking), and context specificities such as the built environment, cultural norms, and income levels, all of which shape travel behaviour. Depending on these factors, the authors conclude that shared mobility can both mitigate and exacerbate the environmental impacts of passenger transport, highlighting the importance of local governments in shaping these outcomes through policy-making.

Built environment

Another impact of shared mobility discussed in the literature relates to the built environment, which encompasses all human-made physical structures, including buildings, transportation networks, and public spaces where daily activities take place (Martinez et al., 2024). A recurring theme is the potential of shared mobility to reduce parking demand and enable the reallocation of urban space, particularly as it may contribute to lower levels of private car ownership (Diana and Chicco, 2022; Martinez et al., 2024). By decreasing the need for parking and the space devoted to idle private vehicles, shared mobility can create opportunities for public authorities to repurpose urban areas for more productive uses, ultimately enhancing urban livability (Tsavachidis and Petit, 2022).

Urban mobility, accessibility and equity

Across the literature, there seems to exist an agreement that shared mobility, when properly deployed, has shown the potential to improve accessibility and equity (Shaheen et al., 2017; Martinez et al., 2024). This potential stems from, first, the ability of these services to provide on-demand, flexible travel options that can bridge gaps left by conventional public transport, particularly in low-density or poorly served areas where fixed-route services are often costly or infrequent (Martinez et al., 2024); second, the reduction of the need to own a private vehicle, lowering financial barriers associated with purchase and maintenance (Zhu et al., 2023); third, because of the potential of its interactions with public transport. Effectively integrating flexible (but low-capacity) shared mobility services with traditional public transport (typically high-capacity but provided more rigidly) can generate synergies that address the limitations of both systems while improving overall service quality.

In particular, shared mobility can enhance first- and last-mile connectivity by facilitating access to public transport hubs, acting as a feeder service in low-density areas, and providing last-mile connections to final destinations. This integration can extend the reach of transport networks, increase the attractiveness of public transport, expand its catchment areas, and promote intermodal travel behaviour (Kapuku et al., 2021; Tuffour, 2022; Horjus et al., 2022; Zhu et al., 2023; Martinez et al., 2024). These synergies can be further amplified by the emergence of mobility as a service (MaaS) systems, which integrate shared mobility services and traditional public transport within a single digital platform, allowing users to plan, book, use, and pay for their trips in a seamless manner (Hensher et al., 2021; Martinez et al., 2024).

However, the relationship between shared mobility and public transport does not necessarily promote a sustainable transport network. In the absence of appropriate regulation, shared mobility services may compete with public transport by attracting its users and increasing the number of vehicles on the road. This, in turn, can exacerbate transport-related externalities (Zhu et al., 2023). The same happens when we are talking about accessibility and equity in urban mobility. Despite its potential to improve accessibility and reduce disparities, there are some equity challenges that

lead these services to often fail to deliver these equitable promises (Martinez et al., 2024). For example:

- Private operators tend to locate vehicles where demand and profitability are highest, typically central, high-density districts, usually wealthier areas with better public transport access and a less public transport-dependent population, leaving peripheral or low-income neighbourhoods underserved, exacerbating transport inequity (Martinez et al., 2024; Coenegrachts et al., 2024; Gao and Li, 2024);
- Shared mobility services are, typically, more prevalent among younger, better educated, and higher-income individuals, while older adults, low-income households, community minorities, and residents of peripheral areas are under-represented across carsharing, ridesourcing, and bikesharing platforms (Shaheen et al., 2017; Martinez et al., 2024);
- The digital prerequisites of most platforms, such as smartphone ownership, Internet access, and credit-card payment, further exclude segments of the population that lack these resources, creating a barrier for users who lack digital literacy and digital banking services, especially among low-income and elderly populations (Shaheen et al., 2017; Leat et al., 2022; Martinez et al., 2024).

Shaheen et al. (2017) present a comprehensive framework on transportation equity barriers, shared mobility challenges, and opportunities. A summary of the STEPS (Spatial, Temporal, Economic, Physiological, and Social) framework, provided by the authors, can be found in Table 2.1.

Fully realizing the potential of shared mobility requires addressing the complex challenge of integrating diverse services into existing transport systems while ensuring social, environmental, and economic sustainability. In this context, data-driven policy-making becomes essential, as it enables the systematic assessment of impacts, benefits, and trade-offs across different scenarios. Such an approach supports more informed decision-making in transport planning, policy design, and infrastructure development, ultimately contributing to more effective solutions that maximize benefits while minimizing externalities. This topic is further explored in the following section.

2.3 Data-driven policy-making

Transport planners aim to improve the performance of transport systems through the implementation of policies (Wee et al., 2011). The goal of this section is to understand what policy-making is (Subsection 2.3.1), and how it can be designed and implemented to integrate shared mobility modes within a sustainable (environmentally, economically, and socially) transport system, aligned with government goals. This is done by presenting a literature review on the motivations of these policies, types of policies, and mechanisms to effectively design and implement them

Table 2.1: STEPS to transportation equity by Shaheen et al. (2017)

Transportation Barriers	Definition	Shared Mobility Opportunities	Shared Mobility Challenges
Spatial	Spatial factors that compromise daily travel needs (e.g., excessively long distances between destinations, lack of public transit within walking distance)	(i) Public transit operators and ridesourcing first- and last-mile partnerships; (ii) Microtransit for lower-density areas	(i) Higher operating costs in lower-density exurban and rural settings; (ii) Limited curb space for increasing variety of mobility services
Temporal	Travel time barriers that inhibit a user from completing time-sensitive trips, such as arriving to work (e.g., public transit reliability issues, limited operating hours, traffic congestion)	(i) Dynamic microtransit; (ii) Late-night ridesourcing and shuttle services; (iii) Commuter carpooling services	(i) Wait-time and travel-time volatility on congested roadways; (ii) Unpredictable wait times due to supply fluctuations
Economic	Direct costs (e.g., vehicle ownership, fares) and indirect costs (e.g., smartphone, Internet, credit card access) that can create economic hardship and hinder basic travel.	(i) Shared mobility subsidies for low-income users; (ii) Multiple payment options for shared mobility services; (iii) Multi-modal hubs with Wi-Fi access	(i) Credit/Debit Card payment; (ii) High cost for longer distance and peak-demand trips; (iii) Maintaining affordability, while providing livable wages
Physiological	Physical and cognitive limitations that make using standard transportation modes difficult or impossible (e.g., infants, older adults, and disabled)	(i) Older adult-focused shared mobility services; (ii) Voice-activated mobility app features	(i) Maintaining legacy technology access; (ii) Ensuring adequate driver training
Social	Social, cultural, safety, and language barriers that inhibit a user's comfort with using transportation (e.g. neighborhood crime, poorly targeted marketing, lack of multi-language information)	(i) Ridesourcing app interface that minimizes sociodemographic profiling; (ii) Targeted outreach to low-income and minorities; (iii) App information in user's native language	(i) Attracting marginalized groups; (ii) Driver prejudice against riders; (iii) Providing security at unmanned vehicle stations

(Subsection 2.3.2). The assessment of the outcomes of these policies is equally important to maximize benefits, compare different scenarios, and minimize externalities; therefore, a review on policy evaluation is presented at the end of this chapter (Subsection 2.3.3).

2.3.1 Policy concept

Firstly, it is essential to understand what is meant by policy in the literature. Marsden and Reardon (2017) present a comprehensive analysis on the concept of policy (see Table 2.2), aiming to help understand the different aspects of a policy that can be under investigation, presenting the definition of Howlett and Cashore (2009) of a policy consisting of a "complex regime of ends and means-related goals (more abstract), objectives (less abstract), and settings (least abstract)".

Table 2.2: Howlett and Cashore Policy Taxonomy by Marsden and Reardon (2017) adapted from Howlett and Cashore (2009)

Policy focus	Policy content		
	High level abstraction	Programme level operationalization	Specific on-the-ground measures
Policy ends or aims	Goals: What general types of ideas govern policy e.g., economic growth	Objectives: What does policy formally aim to address? e.g., reduction in congestion	Settings: What are the specific on-the-ground requirements of policy? e.g., specific targets, such as 'increase travel speed by x percent'
Policy means or tools	Instrument logic: What general norms guide implementation preferences? e.g., welfare maximisation	Mechanisms: What specific types of instruments are utilized? e.g., competitive infrastructure funding	Calibrations: What are the specific ways in which the instrument is used? e.g., peak pricing premium

For better clarity, within the scope of this project, when talking about policies, it will refer to means (i.e., policy levers, mechanisms, tools) that policy-makers have to achieve certain pre-defined ends (i.e., goals/objectives). In the transportation context, these policies include infrastructure investments (e.g., roads, bike lanes, railways, etc.), pricing mechanisms (such as fuel taxes, public transport subsidies, and road pricing), land-use regulations, and specific public transport policies (e.g., service frequency and timetables), as well as information and communication initiatives. Such policies can yield a wide range of impacts, affecting travel times and reliability, accessibility, safety, environmental outcomes, and costs for the public sector, companies, and users (van Wee and Mouter, 2021).

2.3.2 The role of policy-making in the shared mobility context

In the context of shared mobility, Zhu et al. (2023) propose a framework that links users, service providers, and government actors, highlighting the central role of policy-making in achieving sustainable transport systems. Within this framework (see Figure 2.4), government interventions influence both the demand side, this is, the travel behaviour – taking into account the understanding of different aspects, such as, mode choice (i.e., the factors that influence the decision travelers make among alternatives modes), travel patterns (i.e., frequency, origin-destination pairs, trip length, and time-of-day of shared-mobility trips), attitude (i.e., perceptions, beliefs, and concerns about shared-mobility), vehicles choice (i.e., the type of vehicle users select, for example, gasoline vs electric) and user characteristics (i.e., socio-demographic and economic traits such as income, age, gender, education, car-ownership status, and disability) – and the supply side of mobility services where key aspects such as fleet size, demand estimation, resource allocation, pricing strategies, and operational models are taken into account by the companies. These policy interventions span several key areas, including integration with public transport (i.e., promoting synergies and reducing substitution/competition), operational regulation (e.g., market entry, service type, facility scale, pricing and subsidy schemes), and infrastructure regulation (e.g., parking spaces, road construction, charging infrastructure, etc.).

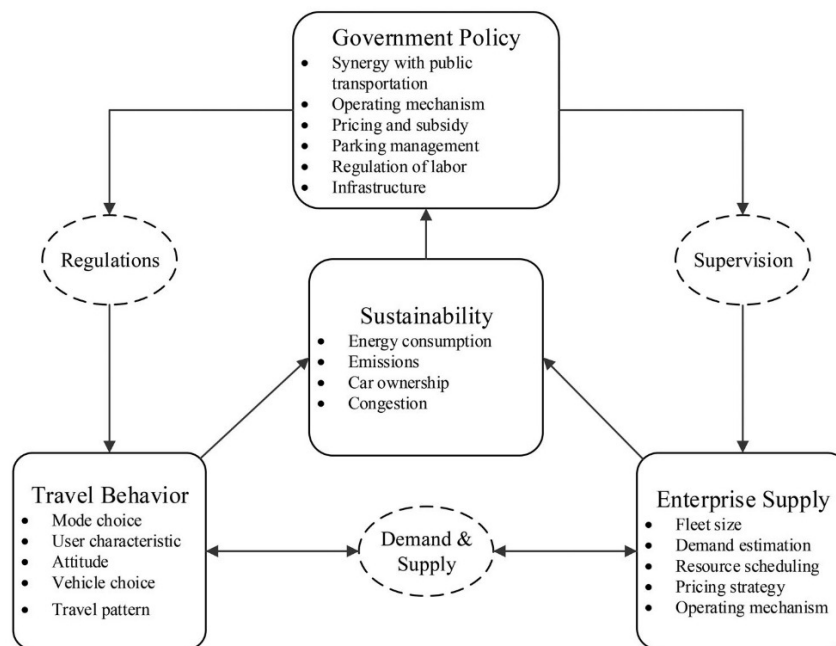


Figure 2.4: General framework of sustainable shared mobility systems by Zhu et al. (2023)

Guan et al. (2025) extend this perspective by presenting a comprehensive literature review of how incentives (policy levers) can be used to promote a sustainable operation of shared-mobility services and accelerate their adoption. This analysis is done in a three-step structure, answering the "why", i.e., the policies' functions that support a sustainable operating shared mobility system, the

"what", i.e., a classification of the different types of incentives, and the "how", i.e., the mechanisms to implement them.

The “Why”

Starting with the motivations behind these policies, the authors present two critical policy functions. First, to enhance the attractiveness of shared mobility services for both demand and supply sides, in order to scale the shared mobility market. Second, to coordinate demand-supply matching to improve availability by optimizing resource allocation and enhancing service coverage through spatial redistribution – set of incentives that encourage users or operators to move vehicles from areas of surplus to areas of shortage – or temporal adjustment – set of incentives that shift user demand or driver supply to ensure that the system does not collapse under the weight of excessive peak demand or become wasteful during idle time.

Overall, these policy levers shape the behavior of shared mobility systems’ stakeholders – enhancing the attractiveness for travelers, and service suppliers, acting as cost-friendly and benefit-effective solutions to challenges encountered – supporting the long-term viability and reliability of shared mobility systems, and promoting a system aligned with broader environmental and societal goals, such as the focus of this thesis, the improvement of urban mobility and accessibility with an equitable distribution of impacts.

The “What”

The authors classify incentives (policies) according to two categories (see Figure 2.5):

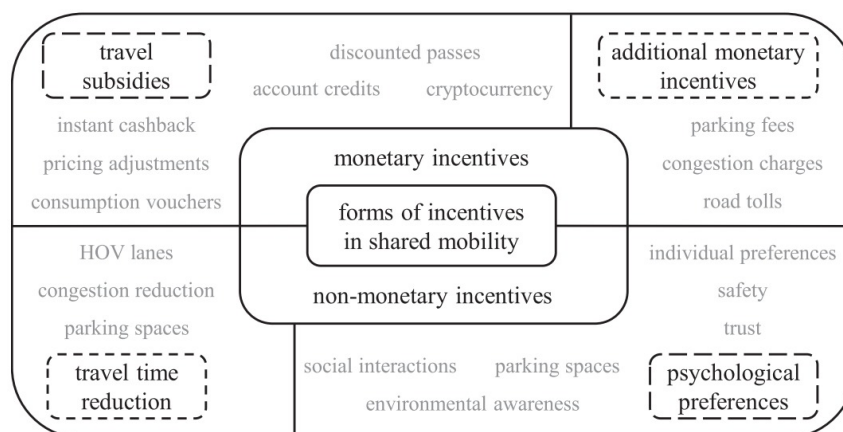


Figure 2.5: The framework of forms of incentives by Guan et al. (2025)

Monetary incentives are financial rewards that serve as tools to enhance user participation and satisfaction, including travel subsidies (e.g., discounted passes or pricing adjustments applied to the charges on the demand side and compensation to the supply side) or monetary incentives not related to traveling itself, such as free or discounted parking fees.

Non-monetary incentives cannot be quantified in financial terms; they address other factors that influence the usage of shared mobility, such as travel time, convenience, psychological concerns (e.g., perceived safety, environmental awareness), and trust in the performance of shared mobility services. High-Occupancy Vehicle (HOV) lane access, dedicated bike lanes, reserved parking spots, well-lit bike lanes, or docking stations near major destinations are some examples of these types of incentives.

Guan et al. (2025) provide an extensive review on studies with empirical evidence of the effectiveness of a wide range of incentive types applied to the particular context of different shared mobility services. See, for example, the work of Lloret-Batlle et al. (2017) on the impact of travel time savings from HOV lanes access on users' utility of the ridesharing system. In addition to academic studies, Guan et al. (2025) also review real-world incentive schemes implemented by mobility companies and public authorities. For instance, France enabled local authorities to develop dedicated carpooling lanes for low-emission vehicles, while Italy introduced tax incentives to support carpooling operators (UNECE, 2020).

The “How”

The effectiveness of these policy levers is highly dependent on how they are designed and implemented (Guan et al., 2025). The authors present a two-step framework for the mechanism behind policy-making. The first step consists of characterizing the user behavior, i.e., understanding the factors that are mostly relevant to influence responsiveness to incentives from both users and providers of shared mobility services in the particular context of a given demographic group, shared mobility service, and incentive goal. Three categories of factors are identified: economic, spatio-temporal, and psychological factors. For travelers, economic factors include, for example, the net travel cost after accepting the incentive, while for providers, these include, for example, the monetary income that can be earned from providing the service and offered incentives (Bian et al., 2020; Zhang et al., 2023). Spatio-temporal factors include, for example, the traveler's waiting time for vehicle pickup, the in-vehicle travel duration, and any addition/reduction on time or distance incurred as a result of the incentive. From the travelers' perspective, psychological factors include, for example, perceived safety, comfort, and convenience.

The second step involves determining the appropriate design of incentives, including their timing, target groups, and strength (i.e., the amount). If incentives are set too low, they may fail to generate sufficient engagement, limiting their effectiveness and preventing the achievement of policy goals. Conversely, excessively high incentives may lead to short-term increases in participation but can result in unsustainable costs for service providers over time. Therefore, the key challenge lies in designing incentive mechanisms that balance efficiency for providers with benefits for users, supporting both immediate effectiveness and long-term system sustainability. To address this challenge, several methods have been explored, including the rule-based approach, simulation-based optimization, static optimization, dynamic optimization, bidding auction, and game theory.

For examples of applications of these methods see Angelopoulos et al. (2018) (rule-based approach), Song et al. (2021) (simulation-based optimization), Stokkink and Geroliminis (2021) (static optimization), Xu et al. (2022) (dynamic optimization), Cheng et al. (2021) (bidding auction) and Wang et al. (2023) (game theory).

2.3.3 How to evaluate policy outcomes: Cost-Benefit Analysis vs Multi-Criteria Analysis

The focus of this thesis is equity-aware policy-making regarding shared mobility, with the particular focus on equitable accessibility improvement in urban mobility. Now that we have analyzed the characteristics, opportunities, and limitations of shared mobility services, understood the importance of the role of policy-making, understood what these policies are, what types of incentives can be provided, and how they should be designed and implemented to produce efficient results, it is now time to understand how to evaluate these policy outcomes and what are the current most used methods that help policy-makers and transport planners compare different policies, assess their impact, and make better decisions.

In the literature, when discussing ex-ante evaluations of transport policy options, two methods often arise: Cost-Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA) (Thomopoulos et al., 2009; Wee et al., 2011; Lucas et al., 2016). As already mentioned in Subsection 2.1.2, regarding the utilitarianism theory of equity, the CBA is the most commonly used method in transport-related decision-making (Lucas et al., 2016). However, since the CBA does not differentiate among different beneficiaries of a policy, and only focuses on the aggregate welfare, assessing equity outcomes relying solely on the CBA can be quite limited (Thomopoulos et al., 2009; Lucas et al., 2016). In the light of this limitation, the MCA has been increasingly adopted by transport planners and policy-makers as either a replacement or complement of the CBA (Lucas et al., 2016). The MCA is a multi-objective decision-making approach, where several criteria can be taken into account simultaneously (Thomopoulos et al., 2009). These criteria can be expressed using any indicator of measurement, including monetary terms or quantitative levels of an indicator (Lucas et al., 2016). Different weights can then be set for each criterion, in order to obtain a score for each of them, which are then summed up to provide an overall policy score, providing an overview of candidate policy options (Thomopoulos et al., 2009; Lucas et al., 2016). With these characteristics in mind, the MCA is suggested as the more appropriate method for incorporating equity considerations into transport-related policy evaluations (Thomopoulos et al., 2009).

Chapter 3

Framework for designing equity-aware shared mobility policies

As discussed in the previous chapter, shared mobility services have the potential to improve urban mobility systems in several ways. First, they can provide flexible, on-demand travel options capable of bridging gaps left by conventional public transport, particularly in low-density or poorly served areas where fixed-route services are often costly or infrequent. Second, they may reduce the need for private vehicle ownership and use. Third, when properly integrated with public transport, shared mobility services can enhance first- and last-mile connectivity, extend the catchment areas of existing networks, facilitate intermodality, and increase the overall attractiveness of public transport.

However, the literature review indicates that fully realizing this potential entails significant challenges. If poorly planned or insufficiently regulated, shared mobility services may reinforce existing inequalities by concentrating in central, high-demand, and more profitable areas, while leaving peripheral or socially vulnerable territories underserved. They may also compete with public transport rather than complement it, potentially increasing transport-related externalities. In this context, several questions arise: how can public authorities, policy-makers, and transport planners integrate shared mobility services into the existing transport network? Can these services be used to promote a more equitable increase in accessibility? And how can shared mobility policies be designed while ensuring a socially and economically sustainable transport system? These questions motivate the work developed in this thesis: the development of a methodological framework that serves as a tool to support policy-makers and transport planners in decision-making regarding the location of shared mobility services. The proposed approach aims to improve accessibility from a vertical equity perspective by evaluating whether shared mobility services can support accessibility improvements in disadvantaged areas that are more mobility-vulnerable.

The purpose of this chapter is to bridge the lessons obtained from the literature review with the methodological framework proposed in this thesis. Section 3.1 presents a conceptual framework that synthesizes the main relationships between shared mobility, accessibility, equity, and data-driven policy-making. This framework provides the conceptual basis for understanding how

shared mobility services can support more equitable urban transport systems, while also highlighting the need for careful planning and policy intervention.

Building on this conceptual framework, Section 3.2 focuses on a specific decision-making problem: the location of shared mobility services from a vertical equity perspective. This location problem serves as a proof of concept for operationalizing the broader conceptual framework through a data-driven methodology.

3.1 Conceptual framework

There is a vast body of literature covering the following topics: accessibility and equity in urban mobility; the emergence of shared mobility, with its opportunities and necessary cautions; and transport-related policy-making. However, to the best of our knowledge, there is no complete framework that brings all of these themes together – in a clear yet detailed way – to support transport planners and policy-makers in improving urban mobility through data-driven approaches. The objective of this section is, therefore, to synthesize the main insights derived from the preceding sections of this literature review, establishing a knowledge base that supports the remainder of this thesis.

Literature Review: key insights

Urban mobility is currently at the center of multiple ongoing transformations, including digital and environmental transitions, as well as evolving travel needs driven by population growth and urban expansion. In this context, emerging mobility services, particularly shared mobility, have been identified as promising solutions to improve transport systems.

The literature highlights that shared mobility can have several positive impacts. These include reducing environmental impacts associated with transportation (e.g., emissions and energy consumption), improving transport infrastructure efficiency, enhancing public transport attractiveness, mitigating congestion, improving the built environment through the reallocation of urban space currently occupied by idle vehicles or parking spots, and, most importantly in the context of this thesis, enhancing accessibility and reducing disparities in its distribution, thereby promoting equity.

However, these potential benefits are not guaranteed. Their realization depends on effective government intervention through well-designed policy-making. Such interventions should promote synergies with public transport rather than competition, mitigate transport-related externalities, address trade-offs with service providers' profitability, enhance the attractiveness of shared mobility services for both users and operators, and ensure efficient system operation through improved demand–supply matching. Ultimately, policies must contribute to a transport system that is environmentally, economically, and socially sustainable.

For policy-making to be effective, policy goals must be defined with an understanding of the current state of the transport system, and policy outcomes must be evaluated within a list of candidate policies. For that, data-driven approaches are essential. Implementing a data-driven

policy-making approach requires a clear conceptualization of accessibility, including its four components: land-use (available opportunities), transport (travel time, costs, effort), temporal (time restrictions), and individual (needs, abilities, opportunities) components. At the same time, equity must be considered, acknowledging its different dimensions (e.g., horizontal, vertical, spatial, and territorial equity) and the underlying normative frameworks (e.g., utilitarianism, egalitarianism, and sufficientarianism) that guide policy priorities. Beyond conceptual understanding, it is necessary to operationalize these concepts through appropriate measures. In the case of accessibility, different types of measures – such as infrastructure-based, location-based, person-based, and utility-based indicators – capture different dimensions of the concept and should be selected according to the objectives of the analysis. Similarly, equity can be assessed through a range of indicators, including the Lorenz Curve and Gini coefficient, the Theil index, and the Palma ratio, each with its own strengths and limitations.

Finally, evaluating policy outcomes is a critical step in supporting informed decision-making. While cost-benefit analysis (CBA) remains widely used in transport planning, it often fails to capture distributional effects. In contrast, multi-criteria analysis (MCA) provides a more suitable framework for incorporating multiple objectives – such as accessibility, equity, and environmental impacts – allowing a more comprehensive assessment of policy alternatives.

A visual representation of this summary can be found in Figure 3.1.

3.2 Data-driven framework for locating shared mobility services

As discussed in the previous chapter, data-driven policy-making is essential to maximize the benefits of shared mobility services, minimize their externalities, and address the complex challenge of integrating them into existing urban transport systems. A complete understanding of the current state of the transport network, characterized by proper accessibility measures and equity indicators selected in alignment with the policy-maker objectives, is essential for the design of effective policies and infrastructure development. The challenge is therefore to operationalize these principles into a single approach that remains easy to interpret and communicate, while also accounting for data availability and practical implementation constraints.

Building on the work of Junyent et al. (2024), where a methodological framework was developed combining Multi-Criteria Decision Analysis (MCDA) and Geographic Information Systems (GIS) to plan the future locations of shared mobility hubs, the work on this thesis proposes a methodology aimed at supporting policy-makers and transport planners in the location of shared mobility services, to promote an increase of accessibility through the lens of vertical equity, this is, focusing on social inclusion and prioritizing the improvement of accessibility for disadvantaged individuals/regions facing greater mobility-related vulnerability.

To achieve this, the methodological framework relies on GIS-based analysis and heatmaps to identify priority areas for intervention, using a flexible set of criteria that can be adapted to specific policy objectives and local planning priorities. By incorporating both accessibility and socio-spatial vulnerability indicators (demographic and socioeconomic), this framework provides

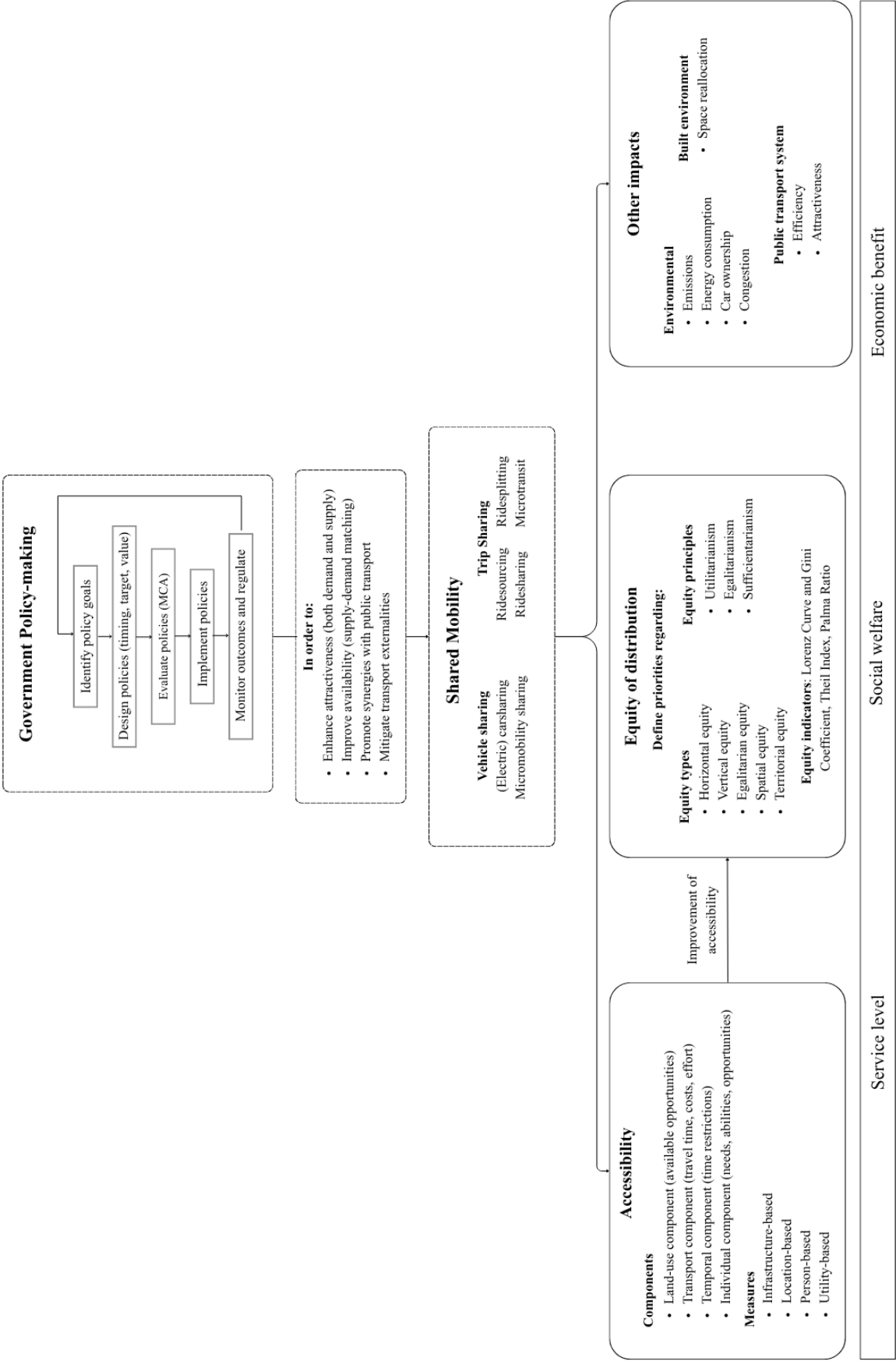


Figure 3.1: Data-driven policy-making for equity-aware shared mobility: a framework

a decision-support tool for identifying priority areas for deploying shared mobility services and contributes to a more equity-oriented planning process.

The proposed methodology is structured into four main steps:

1. Relevant geospatial and transport data are collected and prepared, including spatial information about the study area, public transport networks, potential locations for shared mobility infrastructure, demographic and socioeconomic variables required to characterize accessibility-related vulnerability;
2. The current state of mobility of the study area is analyzed. This step corresponds to the AS-IS scenario and aims to understand the level of accessibility provided by the existing public transport system and the equity of its distribution among the living population (horizontal equity evaluation);
3. Priority intervention areas are identified through the design of GIS-based heatmaps. These heatmaps combine a set of criteria that allows policy-makers to identify areas where shared mobility services could be more relevant from a vertical equity perspective;
4. Alternative policy scenarios are simulated and their impact assessed, to evaluate accessibility improvements, identify benefited areas, and analyze trade-offs between accessibility gains, equity-oriented prioritization, spatial coverage, and investment requirements.

A visual representation of this methodology is shown in Figure 3.2.

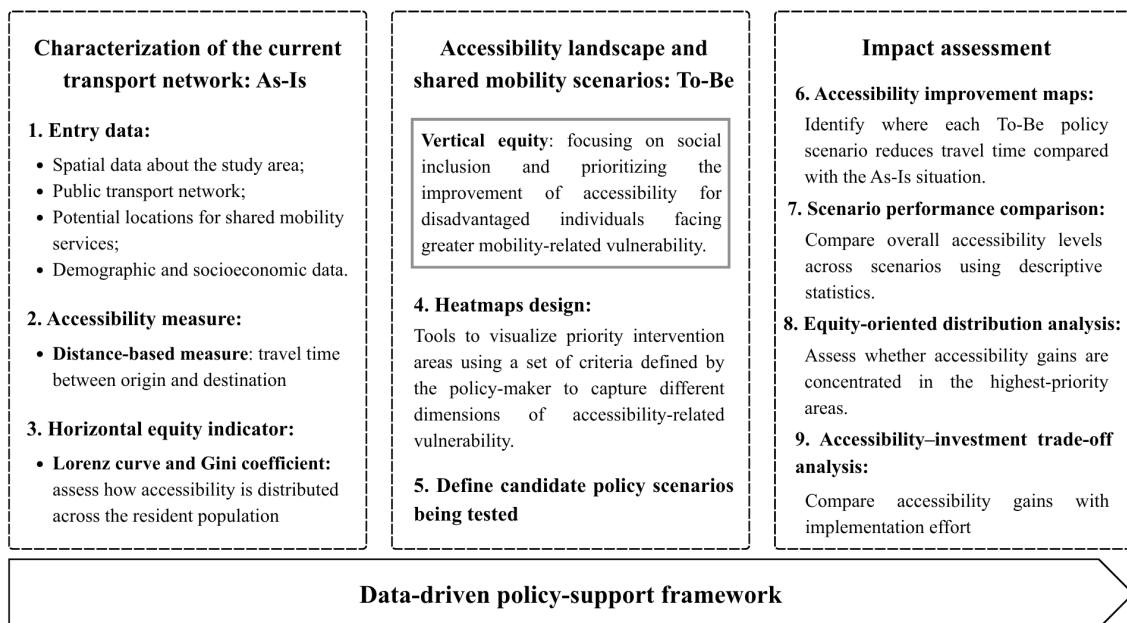


Figure 3.2: Summary of the proposed methodological framework

It is important to emphasize that the proposed methodology does not aim to produce a single optimal solution or prescribe a definitive implementation policy. Instead, it is intended as a decision-support tool that enables the comparison of alternative policy scenarios to support a more

informed and equity-sensitive planning process, helping to evaluate shared mobility services as a potential instrument for reducing accessibility-related vulnerabilities in urban mobility systems.

It is also important to note that this methodological framework can be extended to support other shared mobility decision-making problems. In this thesis, the framework was applied to accessibility improvement from a vertical equity perspective, prioritising areas with greater mobility-related vulnerability. However, the same approach could also be adapted to a horizontal equity perspective, in which the objective would be to distribute these services to as many users as possible.

Chapter 4

Case study: policy-support tool for Porto

This chapter presents the application of the proposed methodological framework to the city of Porto. Building on the concepts and methodological steps discussed in the previous chapter, the case study aims to assess how shared mobility services can be planned as a complementary first- and last-mile solution to the existing public transport network. In particular, the analysis focuses on the potential implementation of electric carsharing hubs and evaluates whether these services can help improve accessibility in areas facing greater mobility-related vulnerability.

The chapter first introduces the context of the case study and the main mobility characteristics of Porto that motivate this thesis. It then describes the data used to support the analysis, including geospatial, transport, demographic, and socioeconomic information. Afterwards, the current accessibility conditions of the public transport network are characterized, forming the As-Is baseline scenario. This is followed by the building of accessibility and priority heatmaps, which support the definition of alternative To-Be policy scenarios. The chapter concludes with an impact assessment of these scenarios, comparing their accessibility gains, spatial distribution of benefits, equity orientation, and relative investment effort.

4.1 Context and motivation

In 2017, the official Portuguese statistics office (INE – *Instituto Nacional de Estatística*) conducted a mobility survey among residents of the Metropolitan Areas of Porto and Lisbon (Instituto Nacional de Estatística, 2018). The survey covered approximately 100,000 respondents and aimed to characterize daily mobility patterns. The results highlighted the strong dependence of metropolitan mobility on private car use. In the Metropolitan Area of Porto, private cars were the main mode of transport for commuting, accounting for approximately 67.6% of all trips across the different days of the week. Porto plays a central role in the metropolitan transport system, being the second-largest municipality in the Metropolitan Area of Porto by total number of trips, with an estimated 419,000 daily trips. Its combination of high mobility demand and dense public transport

infrastructure makes it a challenging case study for assessing the potential contribution of shared mobility services to accessibility improvement and transport network integration. With this context in mind, the municipality of Porto was selected as the case study for the work developed in this thesis.

In this study, the proposed methodological framework was applied to assess the potential impact of introducing electric carsharing hubs in Porto, a shared mobility service currently absent from the city, as a complementary solution to improve access to its main public transport nodes. These nodes were defined as key intermodal connection points where passengers can access public transport services and transfer between different transport modes. Based on this definition, five destinations were considered: *Casa da Música*, *Trindade*, *São Bento*, *Campanhã*, and *Hospital de São João*. The selection of these destinations is directly related to the objective of assessing carsharing as a first- and last-mile solution. By improving connections between residential areas and major public transport nodes, carsharing hubs may reduce total travel times, increase the convenience of multimodal trips, and improve the attractiveness of public transport. The potential role of carsharing as a complementary first- and last-mile solution is particularly relevant in areas where current public transport services provide lower levels of accessibility and where residents may therefore be more likely to rely on private cars.

After collecting the necessary data, the first step of the case study was to characterize the As-Is situation of urban mobility in Porto. This baseline analysis focused on the accessibility provided by the existing public transport network, namely metro and bus services, and on the equity of its distribution among the population living in the municipality.

The second stage involved identifying priority intervention areas using GIS-based heatmaps. These heatmaps were designed using demographic, socioeconomic, and transport-related indicators to identify areas with greater mobility-related vulnerability and to support the definition of several alternative carsharing hub-location scenarios.

Finally, the accessibility impacts of each scenario were evaluated by comparing the resulting To-Be accessibility levels with the As-Is baseline. This comparison enabled the assessment of the spatial distribution of accessibility improvements, identification of the statistical sections benefiting from each scenario, and discussion of trade-offs among accessibility gains, equity-oriented prioritization, and investment requirements. The following sections describe each step of the methodology applied to the case study in greater detail.

4.2 Data collection and preparation

The first step of the methodology consisted of collecting and preparing the spatial, transport, demographic, and socioeconomic data required for the analysis. The objective of this stage was to build a GIS database capable of representing the current urban mobility conditions in the municipality of Porto and supporting the subsequent accessibility and equity analyses.

Census data

Geospatial data for the municipality of Porto were obtained from the 2021 Census, provided by the official Portuguese statistics office (Instituto Nacional de Estatística, 2026). These data correspond to the most recent census information available and are spatially aggregated at the level of statistical sections. In total, the study area was divided into 243 statistical sections, which served as the primary spatial units of analysis. These sections formed the base layer for the GIS analysis, which was conducted in QGIS, a free and open-source geographic information system (QGIS, 2026). The geospatial data input in the software is shown in Figure 4.1.

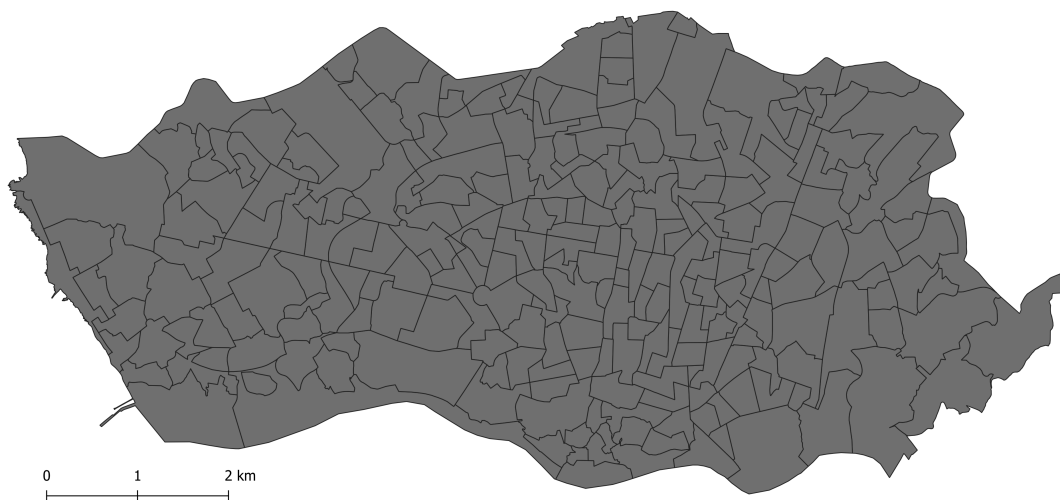


Figure 4.1: The 243 statistical sections composing the city of Porto

For each statistical section, the available census data included information on several dimensions, such as section area, demographic composition by sex and age group, educational attainment, and economic activity status. These variables enabled the study area to be characterized from demographic and socioeconomic perspectives and provided the spatial basis for constructing vulnerability-related indicators.

Transport network data

A second key component of the data collection process concerned the characterization of the existing public transport network. For this purpose, General Transit Feed Specification (GTFS) data were used. GTFS files are a standardized format widely used in transport planning, routing applications, accessibility analysis, and multimodal network modeling (GTFS, 2026). These files contain information on stops, routes, trips, service calendars, stop times, fares, transfers, and route geometries, enabling the representation of both the spatial structure and the scheduled temporal operation of public transport services.

In this study, GTFS data were used to characterize the bus and metro services operating in the municipality of Porto. The bus network considered corresponds to the service provided by STCP, while the metro network corresponds to the metropolitan service operating in Porto. These data enabled mapping the spatial distribution of public transport stops and services across the city and estimating public transport accessibility within the current transport network. GTFS files covering these transport services for the entire Metropolitan Area of Porto are publicly available on *Porto Digital* (Porto Digital, 2026a,c). These files enabled the spatial distribution of bus and metro services across the city of Porto to be visualized, as shown in Figure 4.2.

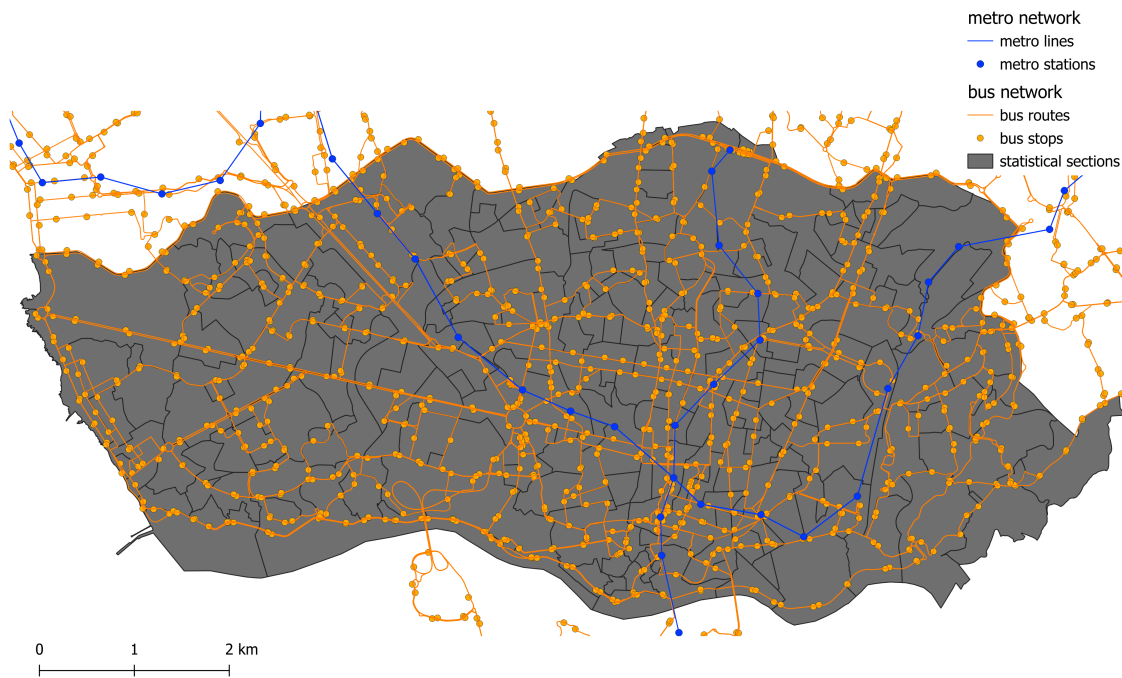


Figure 4.2: Porto bus and metropolitan transport network

Potential hub location data

In addition to the existing public transport system, potential locations for carsharing hubs were identified. This study assumes that existing electric vehicle charging stations, both public and private, can serve as candidate locations for carsharing hubs, as they provide infrastructure that may support the deployment of shared electric vehicles. Public charging station data were obtained from *Porto Digital* as a point geometry layer that contains the locations and characteristics of public electric vehicle charging stations in the municipality of Porto (Porto Digital, 2026b). To complement this dataset, information on private charging stations was obtained from the *MOBI.E* platform (MOBI.E, 2026). Both data sources provide data on the charging infrastructure, including location and additional attributes such as charging power and operator. These datasets allowed the construction of a spatial layer of potential hub locations.

Socioeconomic data

Additional socioeconomic information not available at the statistical section level in the Census data was obtained from the 2017 mobility survey. In particular, this survey was used to derive indicators related to average car availability per household and average household income. The calculation and integration of these indicators are described in greater detail in the following sections.

Overall, this data collection and preparation stage resulted in an integrated GIS database that combines statistical sections, demographic and socioeconomic indicators, public transport supply, and potential locations for shared mobility hubs. This database served as the foundation for the next steps of the proposed methodological framework applied to this case study of the city of Porto.

4.3 Characterization of the current transport network: As-Is

After collecting and preparing the required geospatial data, the second step of the methodology involved characterizing the current urban mobility conditions in the city of Porto. This stage focused on the accessibility provided by the existing conventional public transport network, namely metro and bus services, and on the spatial distribution of accessibility across the statistical sections of the municipality. By measuring current accessibility levels, it is possible to identify areas where the existing public transport system provides lower service levels and where residents may face greater mobility difficulties on their daily trips.

As discussed in the literature review, different accessibility metrics and equity indicators can be used to operationalize these concepts. In this study, accessibility was measured using a distance-based measure, while the equity of its distribution was assessed through the Lorenz curve and the Gini coefficient.

Accessibility measurement - distance measures

Distance-based measures, also referred to as connectivity measures, are a type of location-based accessibility measure that captures the connection between an origin and a destination using indicators such as distance or travel time. In this study, travel time between the origin and destination was selected as the basis for the accessibility metric, rather than travel distance. This choice is supported by evidence in the literature suggesting that, for individuals, travel time is more relevant than distance when choosing a travel mode. Moreover, travel time is generally easier to interpret and more closely reflects people's lived experience of travel than distance (Lovett et al., 2002; Frank et al., 2007; Mavoa et al., 2012).

For this case study, accessibility was defined as the minimum travel time from each statistical section to the nearest major public transport node, accounting for trips made by public transport and walking. The selected destinations correspond to strategic public transport nodes in the city of

Porto, namely Casa da Música, Trindade, São Bento, Campanhã, and Hospital de São João. These locations were considered relevant because they serve as important connection points within the public transport network and facilitate intermodal transfers between transport services. The use of these destinations is aligned with the objective of evaluating carsharing hubs as a complementary first- and last-mile mobility solution. If shared mobility services reduce the travel time between residential areas and major public transport nodes, they may increase the attractiveness of public transport, improve the convenience of multimodal trips, and reduce dependence on private car use, particularly in areas where the current public transport network offers lower accessibility levels.

This accessibility measure was operationalized in QGIS as follows: since the census data used in this study was aggregated within the 243 statistical sections, a point layer was generated using the centroid of each section, with these centroids serving as the origin of the trips to the nearest major public transport node. The travel time between each centroid and the nearest destination was calculated using the QGIS *TravelTime* plugin (TravelTime, 2026). The calculation considered public transport travel by metro and bus and was performed for the morning peak period, between 8:00 and 9:00 a.m. on a weekday, since this corresponds to the time of day during which the highest number of trips is made, according to the previously mentioned mobility survey (Instituto Nacional de Estatística, 2018).

The output of this process was an accessibility value for each statistical section, expressed as the minimum travel time to the nearest major public transport node under the current public transport network. These values defined the As-Is accessibility scenario and provided the baseline for the subsequent analysis. The resulting spatial distribution of accessibility was then used to identify areas with lower access to major transport nodes and to support the construction of priority heatmaps in the subsequent stages of the methodology.

It is important to note that distance-based measures were selected primarily because they are relatively easy to operationalize, require limited data, and are straightforward to interpret and communicate, which was essential given the time and resource constraints of the present study. However, this type of metric also has important limitations. For instance, such measures do not account for individuals' perceptions and preferences, thereby assuming that all opportunities are equally desirable regardless of the destinations' characteristics (Geurs and van Wee, 2004). In this study, all selected destinations were treated as equally relevant major public transport nodes, even though they differ in terms of service frequency, modal diversity, and network role. For example, nodes such as Trindade or São Bento may offer a higher number of services or connections than other locations. Future applications of the methodology could address this limitation by using more robust measures, such as gravity-based measures, capable of incorporating destination attractiveness.

Equity measurement - Lorenz curve and Gini coefficient

After calculating the As-Is accessibility levels for each statistical section, the next step consisted of assessing how this accessibility is distributed across the resident population. For this purpose, the

Lorenz curve and the Gini coefficient were used as indicators of horizontal equity in accessibility provision.

As discussed in the literature review, the Gini coefficient is one of the most widely used equity indicators, largely because of its interpretability and ease of communication to policy-makers and the general public. For the same reasons, this indicator was chosen to assess whether the population of Porto can access key public transport nodes equitably.

The Lorenz curve was constructed by ordering the statistical sections from the lowest to the highest accessibility level and plotting the cumulative proportion of the resident population against the cumulative proportion of accessibility. The resulting curve can be seen in Figure 4.3. The 45-degree line represents a situation of perfect equality. The greater the distance between the Lorenz curve and the equality line, the higher the level of inequality in the distribution of accessibility.

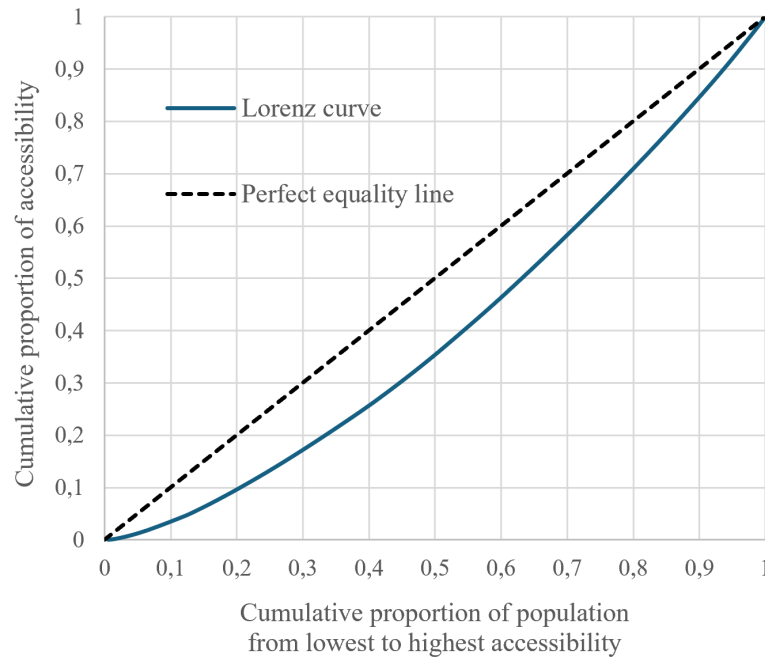


Figure 4.3: Lorenz curve of the distribution of the calculated accessibility among the population of Porto

Due to its complexity, in the literature, the calculation of the Gini coefficient is approximated using the mathematical formulation in Equation 4.1 (Delbosc and Currie, 2011; Shafiq et al., 2024).

$$G = 1 - \sum_{n=1}^N (X_n - X_{n-1})(Y_n + Y_{n-1}) \quad (4.1)$$

In this formula, X_n represents the cumulative proportion of the population, Y_n is the cumulative proportion of accessibility, n denotes each statistical section of the study area, and N represents the total number of statistical sections in the analysis. As discussed in the literature review, the Gini

coefficient ranges from 0 to 1, where 0 indicates a perfectly equal distribution of accessibility, and 1 indicates the highest level of inequality.

Using Equation 4.1, the accessibility level of each statistical section was compared with its resident population to calculate the Gini coefficient. The resulting Gini coefficient for the municipality of Porto was 0.2002. This value suggests a relatively low level of global inequality in the distribution of accessibility to the selected major public transport nodes when considering the combined metro and bus public transport network. The Lorenz curve indicates that approximately 50% of Porto's population accounts for around 35% of the cumulative accessibility provided by the current public transport system.

At first sight, this result suggests that the distribution of accessibility in Porto is relatively equitable, with a Gini coefficient relatively close to 0. However, the reasoning behind these results should be analyzed with caution, taking into account the limitations of the accessibility measure adopted in this study. First, the metric treats all selected major public transport nodes as equally relevant destinations. In practice, these nodes may differ significantly in terms of service frequency, modal diversity, connectivity, and overall attractiveness. For example, stations such as Trindade or São Bento may provide a wider range of services and higher frequencies than other nodes. Therefore, two sections with similar travel times to their nearest node may still experience different levels of effective accessibility depending on the quality and attractiveness of that node. More robust accessibility measures, such as gravity-based measures, can incorporate destination attractiveness and may reveal stronger patterns of inequality. This limitation is highlighted by Shafiq et al. (2024), who show that accounting for the attractiveness of rail stations, measured through service frequency, substantially changes the assessment of accessibility inequality. In their analysis, the inclusion of station attractiveness increased the Gini coefficient for motorized access from 0,29 to 0,47 and for bicycle access from 0,22 to 0,53. This demonstrates that accessibility to transport infrastructure and accessibility to transport services are not necessarily equivalent.

Second, although the accessibility measure used in this study accounts for travel time, it does not directly capture the frequency of public transport services. Two statistical sections may have similar minimum travel times to a major public transport node but very different service levels throughout the day. One section may have frequent services available, while another may rely on routes with low daily frequency. In this sense, travel time alone may overestimate the accessibility conditions of areas where services are less frequent. The importance of incorporating service frequency into public transport accessibility analysis is also emphasized by Mavoa et al. (2012), who show that areas with apparently good accessibility may present much lower levels of effective public transport provision when service frequency is considered. For this reason, frequency was not included directly in the As-Is accessibility metric but was incorporated separately in the subsequent vertical equity analysis.

In conclusion, the Lorenz curve and the Gini coefficient provide an important global measure of horizontal equity in the As-Is public transport network. They allow an overall assessment of how accessibility is distributed across the population, but they do not identify which specific

areas should be prioritized for intervention, nor do they capture additional dimensions of mobility-related vulnerability.

This limitation is particularly relevant in the context of this study, which focus on supporting shared mobility service planning from a vertical equity perspective. Although the Gini coefficient is useful for understanding the overall distribution of accessibility, it is less aligned with the objective of identifying areas where additional mobility solutions may be most needed. For this reason, the proposed heatmap approach was developed.

4.4 Accessibility landscape and shared mobility scenarios: To-Be

After characterizing the As-Is accessibility conditions of the current public transport network, the next step of the methodology was to identify priority areas for implementing carsharing hubs and translate these into alternative implementation policy scenarios.

For this purpose, heatmaps were selected as tools to visualize the accessibility landscape. Two GIS-based heatmaps were designed. The first heatmap was based exclusively on current accessibility levels (accessibility heatmap). The second heatmap (priority heatmap) was constructed using a broader set of criteria. In addition to current accessibility, three complementary indicators were considered: public transport service frequency, average income level, and average car availability per household. These criteria were selected to capture different dimensions of mobility-related vulnerability.

Both heatmaps were then used as decision-support tools to construct alternative hub-location scenarios. The following sections provide a more detailed description of the approach adopted in this case study.

4.4.1 Building the heatmaps

The first heatmap was designed using the As-Is accessibility level of each statistical section. As described in the previous section, accessibility was measured as the minimum public transport travel time between the centroid of each statistical section and the nearest major public transport node. This value was then normalized on a scale from 0 to 1 to make accessibility levels comparable across the study area. A value close to 0 represents sections with shorter travel times to the nearest major public transport node, while a value close to 1 represents sections with longer travel times and, therefore, greater accessibility-related disadvantage. This transformation allows the map to be interpreted as an accessibility-deficit heatmap, in which darker areas indicate sections where intervention may be more relevant from an accessibility-improvement perspective. The resulting accessibility heatmap for the municipality of Porto can be found in Figure 4.4.

The spatial pattern shows that sections with better accessibility are mainly concentrated in the central areas of the municipality and along the main public transport corridors. In contrast, higher accessibility-deficit values are observed in more peripheral areas, particularly in the western and

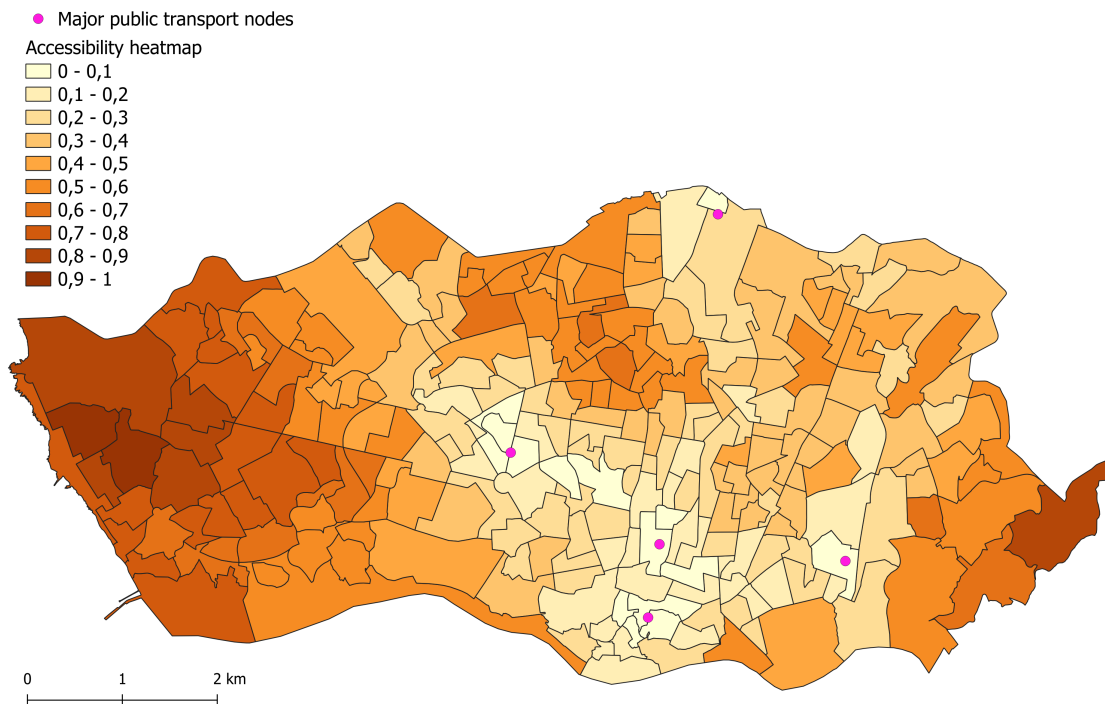


Figure 4.4: Accessibility heatmap

eastern edges of the municipality. These areas are farther from the selected major public transport nodes and therefore present higher minimum travel times under the current public transport network.

To further interpret this spatial pattern, Figure 4.5 overlays the accessibility heatmap with the metro network. This figure highlights an important pattern: many of the sections with lower travel times are located close to the metro line, underlining the important role of the metro network in providing daily accessibility to Porto's population. In contrast, areas located farther from the metro network tend to present higher accessibility-deficit values, suggesting that these areas may be particularly relevant for the implementation of complementary mobility solutions that can strengthen the existing public transport network.

This accessibility heatmap provides policy-makers with a simple and intuitive visual representation of the current distribution of accessibility across the statistical sections of Porto. It allows the identification of areas where the existing metro and bus network provides weaker accessibility and therefore serves as a basis for defining accessibility-oriented hub-location scenarios.

While the accessibility heatmap provides a clear representation of the areas with poorer access to major public transport nodes, this accessibility indicator alone may not fully capture the mobility vulnerability of each statistical section. For this reason, the priority heatmap was developed to support decision-making from a broader equity-oriented perspective. Inspired by the approach of Delbosc and Currie (2011), this priority heatmap combines a set of indicators that reflect different dimensions of mobility disadvantage according to the following four criteria: current accessibil-

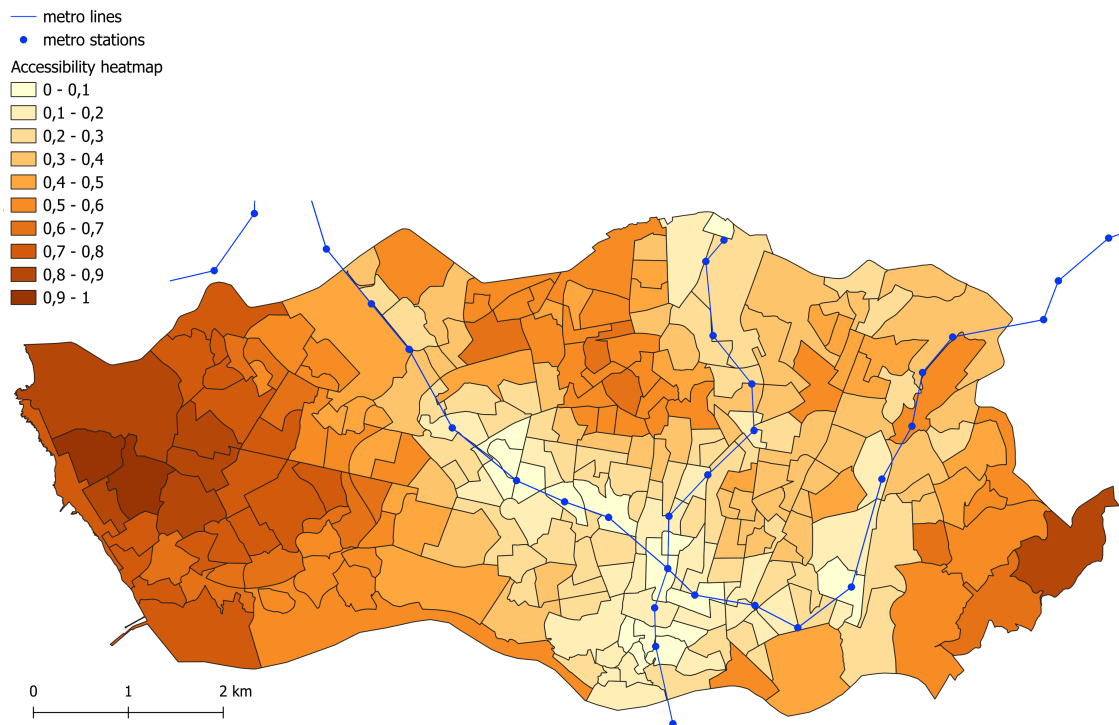


Figure 4.5: Accessibility heatmap and its relation with the metro line

ity level, daily public transport service frequency, average income level, and average number of cars per household. Current accessibility captures the travel-time disadvantage of each section in relation to the selected major public transport nodes. Public transport frequency reflects the level of service available to residents, since areas with fewer services may face greater waiting times, lower flexibility, and weaker public transport attractiveness. Income level was included because lower-income households may have fewer resources to support mobility costs and are therefore more dependent on affordable transport alternatives. Finally, the average number of cars per household was considered because lower car availability may indicate greater dependence on public transport or shared mobility services. The following paragraphs describe in greater detail how these additional indicators were incorporated into the analysis.

Public transport frequency

The public transport frequency indicator was derived from the previously mentioned GTFS files of the bus and metro networks. These files contain information about the public transport system, including stops, routes, trips, timetables, and service calendars. The GTFS data were processed to identify the services operating on the selected reference day, and the output of this process was a point layer containing the estimated number of daily services for each bus and metro stop.

This layer was then imported into QGIS and spatially related to the statistical sections. A first approach consisted of aggregating the services of the stops located within each statistical section. However, this approach presented an important limitation: some sections did not contain

any public transport stop within their boundaries, even though stops were located close to their limits. Classifying these sections as having no access to public transport supply would therefore misrepresent the actual availability of nearby services.

To address this limitation, a proximity-based approach was adopted. The centroid of each statistical section was used as the reference point, and an 800-meter buffer was created around each centroid. This threshold was used as an approximation of a 10-minute walking distance, which was considered a reasonable maximum walking time for an individual accessing a nearby public transport stop. The buffer allowed the analysis to capture public transport stops located in the vicinity of each section, even when they were outside its administrative boundary. Figure 4.6 provides a visual representation of one of the buffers used in this approach.

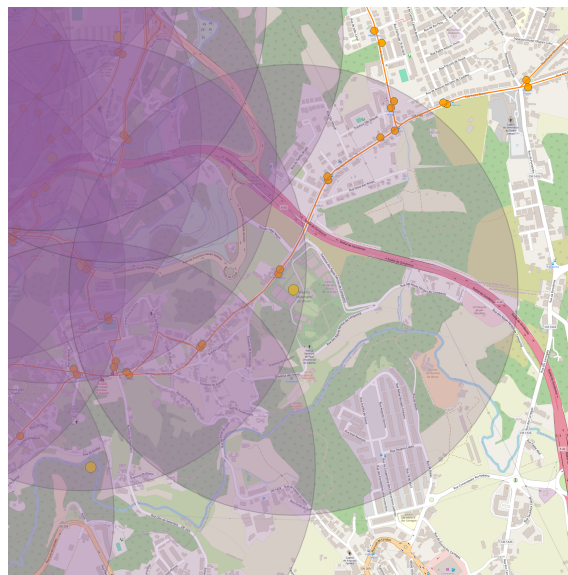


Figure 4.6: Example of the 800-meter centroid buffer used to capture nearby public transport stops. Centroid in yellow, transport stops in orange.

For each centroid buffer, the total number of daily public transport services was calculated by summing the daily service frequencies of all bus and metro stops located within an 800-meter radius. The resulting indicator, therefore, represents the total number of daily bus and metro stop events accessible within walking distance of each statistical section.

Average household income and car availability

Two additional socioeconomic indicators were included in the design of the priority heatmap: average household income and average number of cars per household. These variables were obtained from the 2017 Mobility Survey for the Metropolitan Area of Porto, since they were not directly available in the Census data at the statistical section level.

The income variable was originally provided in income brackets, referring to the average monthly net household income, calculated as the sum of the income of all household members. Since the original data were categorical rather than continuous, each income bracket was converted

into an approximate monetary value in order to estimate average income levels. For closed income intervals, a representative value was assigned based on the midpoint of each bracket. For example, the bracket between €430 and less than €600 was assigned a value of €515, the bracket between €600 and less than €1,000 was assigned a value of €800, and the bracket between €1,000 and less than €1,500 was assigned a value of €1,250. For the open-ended brackets, where no lower or upper bound was available, the closest available threshold was used as the representative value: €430 for households with income below €430, and €7,000 for households with income above €7,000. Although this procedure does not capture the full variation within each bracket, it provides a consistent approximation that allows the income variable to be used in the subsequent quantitative analysis.

Car availability was obtained directly from the survey question concerning the number of light passenger vehicles available to each household. This variable was used to estimate the average number of cars per household in each statistical section.

The mobility survey does not provide the residential location of households at the statistical section level. Instead, survey responses are aggregated into broader mobility zones defined by the survey authors. In the municipality of Porto, four mobility zones were considered: Zone 1, including Aldoar, Foz do Douro and Nevogilde, and Lordelo do Ouro and Massarelos; Zone 2, including Campanhã and Bonfim; Zone 3, including Cedofeita, Santo Ildefonso, Sé, Miragaia, São Nicolau and Vitória; and Zone 4, including Ramalde and Paranhos.

For each mobility zone, the average household income and the average number of cars per household were calculated from the survey data. These values were then assigned to the corresponding statistical sections in QGIS, based on the parish to which each section belongs. As a result, each statistical section inherited the average income and car availability values of its respective mobility zone. The resulting values are presented in Table 4.1.

Table 4.1: Sample size, average household income and car availability by IMob mobility zone

Zone ID	Mobility zone	Sample size	Average cars per household	Average income (€)
1	Aldoar/Foz/Nevogilde + Lordelo do Ouro/Massarelos	1190	1.31	2312.9
2	Campanhã + Bonfim	916	0.90	1606.9
3	Cedofeita/Santo Ildefonso/Sé/Miragaia/São Nicolau/Vitória	1068	0.85	1720.5
4	Ramalde + Paranhos	1114	1.12	1948.1

Composite priority indicator

After calculating the four indicators – accessibility, public transport frequency, income level, and car availability – all variables were normalised on a scale from 0 to 1 and oriented in the same direction. In all cases, a value of 1 represents higher priority for intervention. Therefore, for accessibility, a value of 1 corresponds to the sections with the highest travel time to the nearest major

public transport node. For public transport frequency, a value of 1 corresponds to the sections with the lowest service frequency. For income, a value of 1 corresponds to the lowest average income levels. Finally, for car availability, a value of 1 corresponds to the lowest average number of cars per household.

The composite priority indicator was then calculated as a weighted sum of the four normalised indicators which we called: current accessibility (*A*), public transport frequency (*PTF*), income vulnerability (*IV*) and car availability vulnerability (*CAV*). The mathematical formulation for the calculation of the priority indicator and the weights used can be seen in Equation 4.2.

$$Priority = 0.3A + 0.3PTF + 0.2IV + 0.2CAV \quad (4.2)$$

Sensitivity analysis

To assess the robustness of the selected weights for the composite priority indicator, a sensitivity analysis was conducted to test alternative weighting schemes. This made it possible to evaluate whether the spatial distribution of priority areas was strongly dependent on the chosen weights or whether the main priority patterns remained stable under different assumptions. The alternative weighting schemes tested are shown in Table 4.2.

Table 4.2: Weighting schemes tested in the sensitivity analysis

Weighting scheme	A	PTF	IV	CAV
Baseline	0.30	0.30	0.20	0.20
Alternative 2	0.30	0.50	0.10	0.10
Alternative 3	0.30	0.10	0.50	0.10
Alternative 4	0.30	0.10	0.10	0.50
Alternative 5	0.30	0.20	0.40	0.10
Alternative 6	0.30	0.20	0.10	0.40
Alternative 7	0.30	0.40	0.15	0.15
Alternative 8	0.30	0.10	0.30	0.30
Alternative 9	0.30	0.10	0.40	0.20
Alternative 10	0.30	0.10	0.20	0.40
Alternative 11	0.40	0.25	0.20	0.15
Alternative 12	0.50	0.20	0.15	0.15
Alternative 13	0.60	0.15	0.15	0.10
Alternative 14	0.70	0.10	0.10	0.10

Note: A = accessibility; PTF = public transport frequency; IV = income vulnerability; CAV = car availability vulnerability.

The baseline specification corresponds to the weighting scheme used in the main analysis, where accessibility and public transport frequency were assigned weights of 0.30 each, while income vulnerability and car availability vulnerability were assigned weights of 0.20 each. This choice reflects the central role of accessibility and public transport supply in the objective of the

study, while still incorporating socioeconomic vulnerability and dependence on alternatives to private car use.

Alternatives 2 to 10 keep the accessibility weight fixed at 0.30 and redistribute the remaining weights among public transport frequency, income vulnerability, and car availability vulnerability. These alternatives were designed to assess whether changes in the relative importance of the three complementary vulnerability indicators would significantly affect the priority ranking. Alternatives 11 to 14 increase the weight assigned to accessibility, allowing the analysis to evaluate how strongly the final priority ranking is influenced when accessibility becomes increasingly dominant in the composite indicator.

To compare the baseline with the alternative weighting schemes, the analysis focused on the top 10% of statistical sections with the highest priority scores under the baseline specification, corresponding to the first 24 sections in the ranking. For each of these sections, the difference in ranking position between the baseline and each alternative weighting scheme was calculated. Then, for each section, the average ranking difference across the alternative schemes was computed. Finally, summary statistics (Table 4.3) were calculated for these average ranking differences across the top 10% priority sections.

Table 4.3: Summary statistics of ranking differences for the top 10% priority sections

Sensitivity analysis	Mean	Median	Standard deviation
Alternatives 2–10	3.01	1.67	4.01

Note: Values correspond to the average ranking differences calculated for the top 10% priority sections under the baseline weighting scheme. Alternatives 2–10 only change the weights assigned to public transport frequency, income vulnerability, and car availability vulnerability, while keeping the accessibility weight fixed at 0.30.

For Alternatives 2 to 10, which only modify the weights of public transport frequency, income vulnerability, and car availability vulnerability while keeping accessibility fixed, the average ranking difference among the top-priority sections was 3.01 positions, with a median of 1.67 and a standard deviation of 4.01. These results suggest that the most critical sections identified in the baseline specification remain relatively stable when the weights of the complementary vulnerability indicators are changed. In other words, the priority ranking does not appear to be strongly dependent on small or moderate variations in the weights assigned to these three criteria.

The same procedure was followed for alternatives 11 to 14, in which the weight assigned to accessibility was progressively increased: the analysis focused on the top 10% priority sections under the baseline weighting scheme, corresponding to the first 24 sections in the baseline ranking. For each of these sections, the difference in ranking position between the baseline and each alternative weighting scheme was calculated. Then, the average ranking difference across alternatives 11 to 14 was computed for each section. Finally, summary statistics were calculated for these average ranking differences across the top 10% priority sections.

As shown in Table 4.4, the mean ranking difference increases to 15.31 positions, with a median of 12.50 and a standard deviation of 17.25. These values are considerably higher than those obtained when only the weights of the complementary criteria were varied. This indicates that

changes in the accessibility weight have a much stronger effect on the final priority ranking than changes in public transport frequency, income vulnerability, or car availability vulnerability.

Table 4.4: Summary statistics of ranking differences for the top 10% priority sections under increased accessibility weights

Sensitivity analysis	Mean	Median	Standard deviation
Alternatives 11–14	15.31	12.50	17.25

Note: Values correspond to the average ranking differences calculated for the top 10% priority sections under the baseline weighting scheme. Alternatives 11 to 14 progressively increase the weight assigned to accessibility, while reducing the relative importance of the remaining criteria.

This result confirms the central role of accessibility in the construction of the priority indicator. It also supports the decision to analyze the accessibility heatmap separately from the multi-criteria priority heatmap. An example of the resulting heatmaps for an alternative weighting scheme is shown in Figure 4.7. The remaining sensitivity analysis heatmaps are presented in Appendix A.

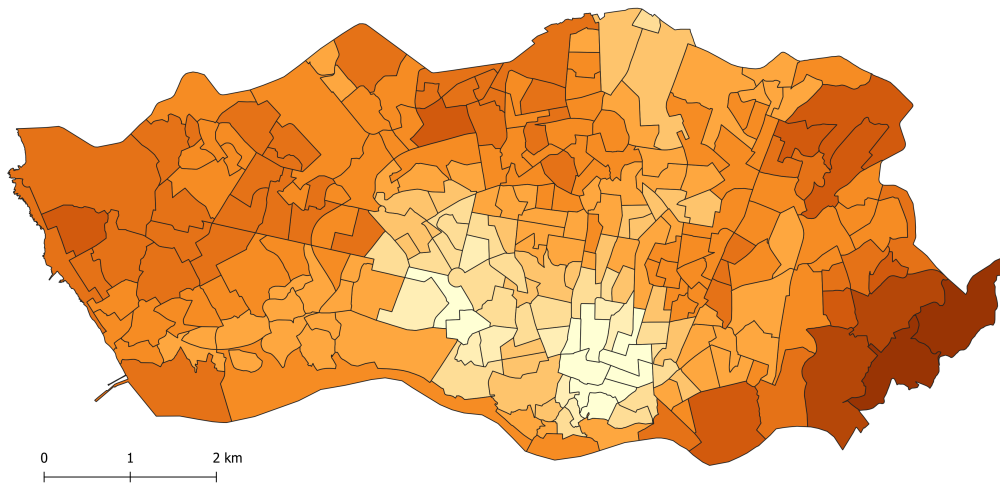


Figure 4.7: Alternative 2: $\text{priority} = 0.3A + 0.5\text{PTF} + 0.1\text{IV} + 0.1\text{CAV}$

The objective of this "priority" indicator is to identify statistical sections experiencing higher levels of mobility-related vulnerability. The resulting priority heatmap therefore supports the identification of intervention areas from a vertical equity perspective, highlighting sections where carsharing hubs may be particularly relevant as a complementary mobility solution. Figure 4.8 presents the resulting priority heatmap.

One possible question regarding the proposed heatmap construction is why population density, or the total number of residents in each statistical section, was not included as a criterion. From a purely efficiency-oriented perspective, prioritising more populated areas could be justified, since accessibility improvements would potentially benefit a larger number of people. However, this

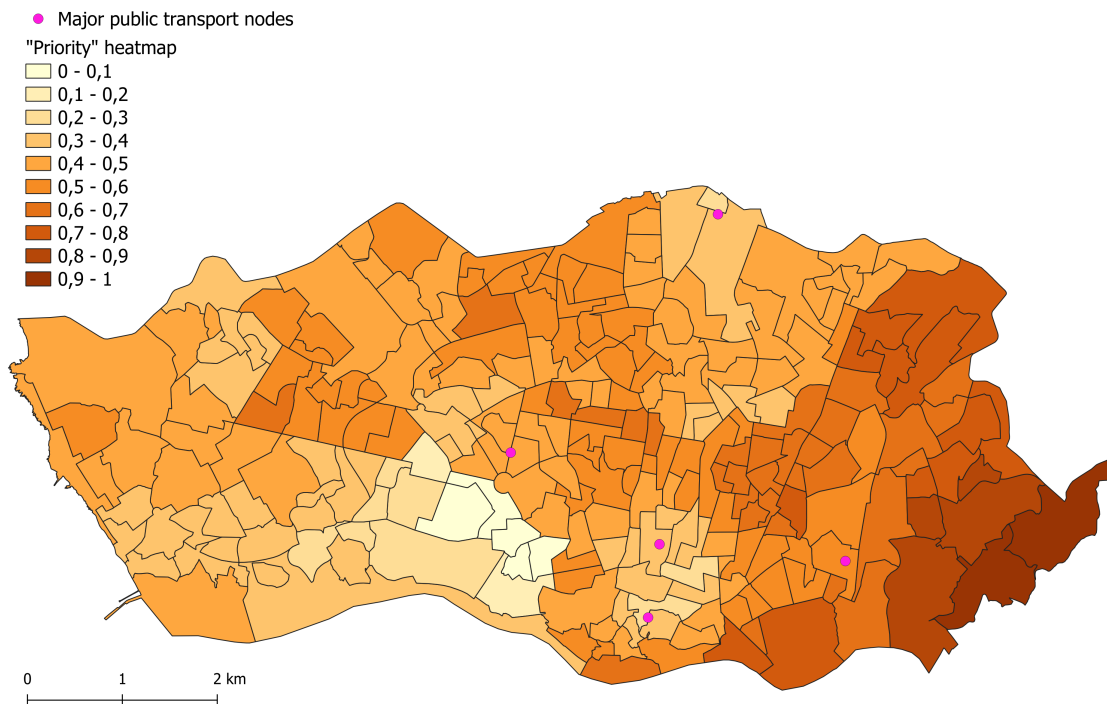


Figure 4.8: Priority heatmap

logic would shift the methodology towards a horizontal equity or accessibility maximisation perspective, where areas with more residents would tend to receive greater priority.

The purpose of the proposed methodology is different. This study adopts a vertical equity perspective, aiming to prioritise areas that experience greater mobility-related vulnerability, even if they are not the most densely populated. Less dense, more peripheral, or more isolated areas may be less attractive for conventional public transport investment, precisely because of lower demand levels. However, these areas may also face greater daily mobility difficulties due to lower accessibility, weaker service frequency, lower income levels, or lower car availability. In this context, this study assesses how more flexible mobility solutions, such as shared mobility services, can be used by policy-makers and transport planners to help address these vulnerabilities.

The following section translates the accessibility and priority heatmaps into alternative car-sharing hub-location scenarios, enabling an assessment of whether these interventions can effectively improve accessibility, address the identified mobility-related vulnerabilities, and support comparisons between different implementation policies.

4.4.2 Shared mobility scenarios: To-Be

Based on the accessibility and priority heatmaps, four alternative To-Be policy scenarios were developed to assess the potential impact of implementing carsharing hubs in the city of Porto. These scenarios differ in terms of the heatmap used to select hub locations, the number and type of infrastructure considered for the deployment of the carsharing hubs, and the spatial distribution of the

hubs. The objective was to enable comparisons on the magnitude of accessibility improvements and the trade-offs between different candidate policies.

The potential locations for carsharing hubs were defined using existing electric vehicle charging stations. This selection was made based on the assumption that these locations would provide existing infrastructure that could support the deployment of shared electric vehicles. Two types of charging stations were considered: public charging stations and private charging stations. Public stations were used as the primary candidate locations, while private stations were introduced in specific scenarios to expand the set of available locations in areas where public infrastructure is limited.

Scenario 1 (Figure 4.9) considers the implementation of carsharing hubs in all available public charging stations in the municipality of Porto. This scenario does not apply a specific equity-oriented selection criterion. Instead, it represents a broad deployment strategy based exclusively on the existing public charging infrastructure. Its purpose is to estimate the potential accessibility gains that could be achieved if all public charging stations were used as carsharing hubs. Therefore, Scenario 1 functions as a reference scenario for assessing the maximum accessibility improvement attainable using only public charging stations.

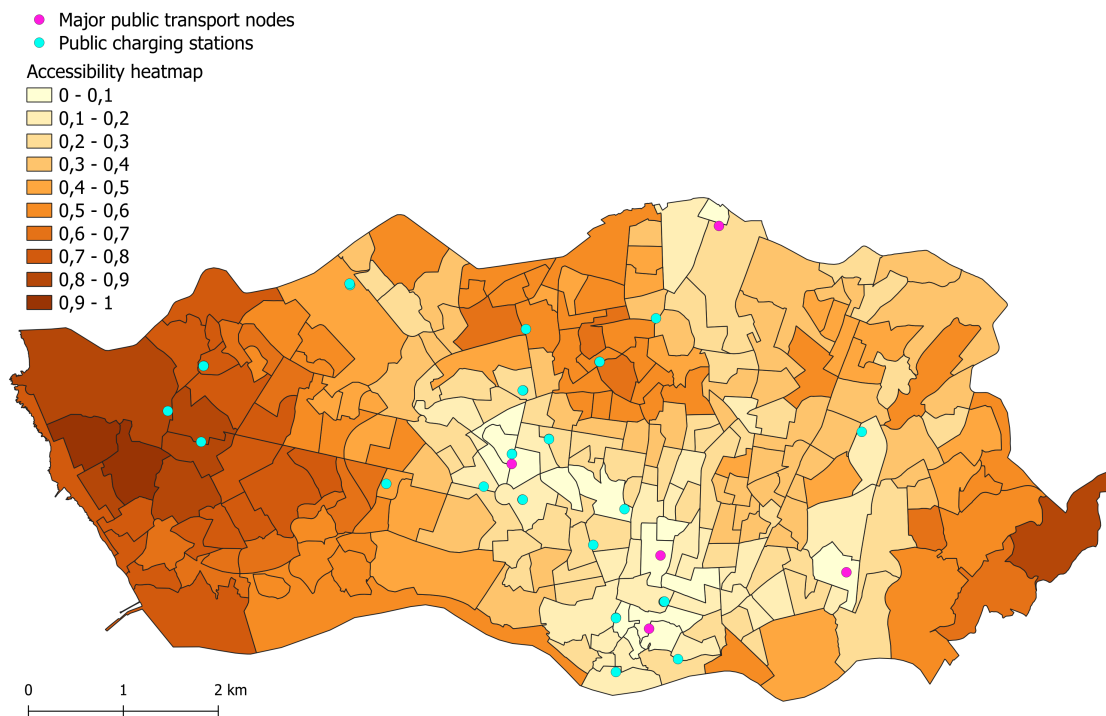


Figure 4.9: Scenario 1

In Scenarios 2, 3, and 4, the number of hubs was fixed at nine. This number was defined as an empirical assumption for the purpose of testing the proposed methodology and comparing different location strategies under the same implementation scale. It should therefore not be interpreted as the optimal number of hubs for the city of Porto. Determining the optimal number of hubs

would require a more complex optimization model that incorporates additional constraints such as expected demand, operational costs, fleet size, land availability, charging capacity, and budget limitations. Since the objective of this thesis is to develop and demonstrate a decision-support framework, rather than to produce a definitive implementation plan, the use of nine hubs provides a simple and comparable proof-of-concept scenario. Future applications of the methodology could integrate optimization procedures to determine both the optimal number and location of hubs according to specific policy objectives and resource constraints.

Scenario 2 (Figure 4.10) considers the implementation of 9 carsharing hubs in public charging stations selected according to the accessibility heatmap. In this case, the objective was to prioritize areas with lower As-Is accessibility to major public transport nodes, while relying only on public charging infrastructure. It also enables analysis of the limitations of relying solely on public charging stations, particularly in areas where such infrastructure is unavailable.

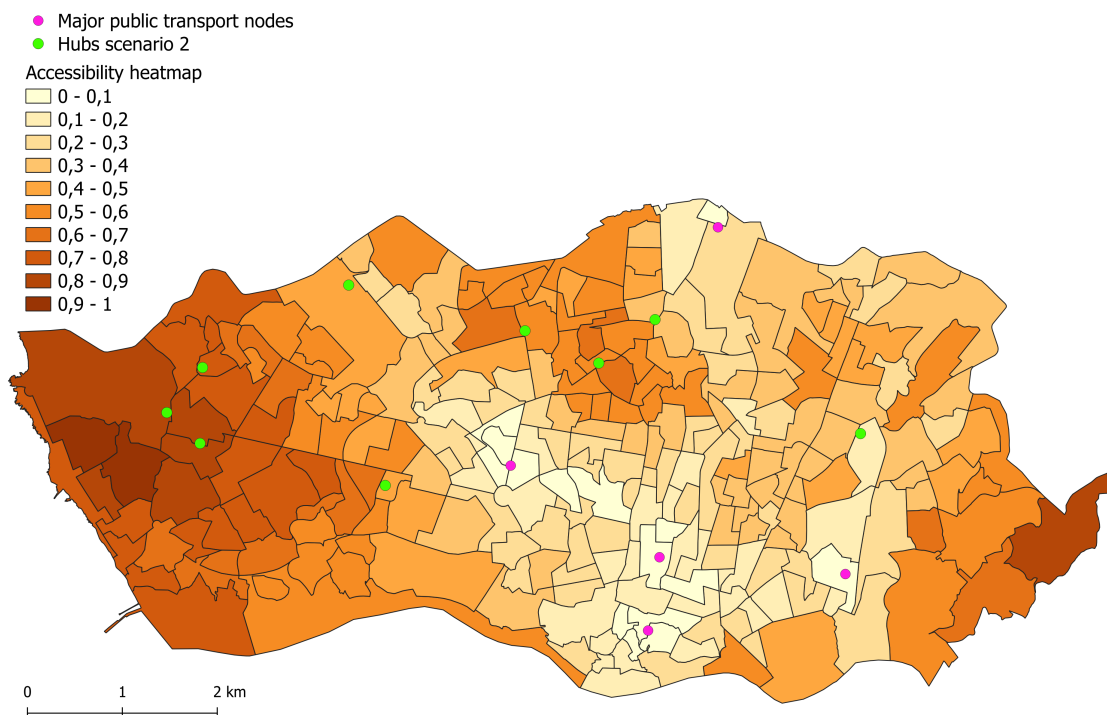


Figure 4.10: Scenario 2

Scenario 3 (Figure 4.11) considers the implementation of 9 carsharing hubs selected according to the priority heatmap. Unlike Scenario 2, this scenario is based on a broader vertical equity perspective, since the priority heatmap combines accessibility, public transport frequency, income vulnerability, and car availability vulnerability. The scenario includes both public and private charging stations. Public charging stations were prioritised whenever possible, while private charging stations were used to address gaps in public infrastructure near high-priority sections.

Scenario 4 (Figure 4.12) also considers the implementation of 9 carsharing hubs using a combination of public and private charging stations, but the selection is based on the accessibility

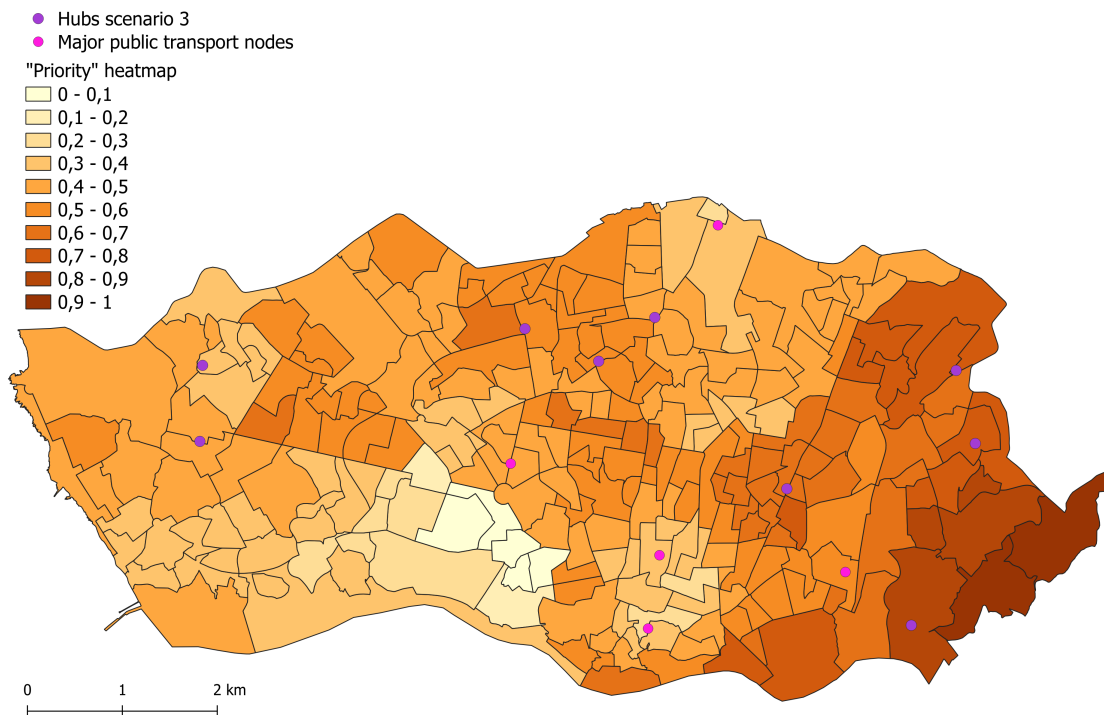


Figure 4.11: Scenario 3

heatmap. The purpose of this scenario is to evaluate whether the inclusion of private charging stations can improve the effectiveness of an accessibility-oriented policy. While Scenario 2 is constrained to public charging stations, Scenario 4 tests whether using both public and private stations allows hubs to be placed closer to areas with poorer accessibility, particularly in parts of the municipality where public charging infrastructure is insufficient.

After defining the four To-Be scenarios, accessibility was recalculated for each statistical section using the QGIS TravelTime plugin. In the As-Is scenario, accessibility corresponded to the minimum travel time by public transport from each section centroid to the nearest major public transport node. In the To-Be scenarios, accessibility was recalculated by considering the possibility of using carsharing as an intermediate mobility solution. For each statistical section, the carsharing-based travel time was calculated as the time required to travel from the section centroid to the nearest carsharing hub using public transport, followed by the travel time from that hub to the nearest major public transport node by car. This value represents the potential accessibility provided by the carsharing hub network under each scenario.

However, the final accessibility value assigned to each section in each To-Be scenario was not assumed to be automatically equal to the carsharing-based travel time. Instead, it was obtained by comparing the As-Is public transport travel time with the carsharing-based travel time. If the carsharing option resulted in a lower total travel time, the section was assumed to adopt the carsharing alternative, and the To-Be accessibility value corresponded to this improved travel time. If the carsharing option did not reduce travel time, the section was assumed to maintain the existing public

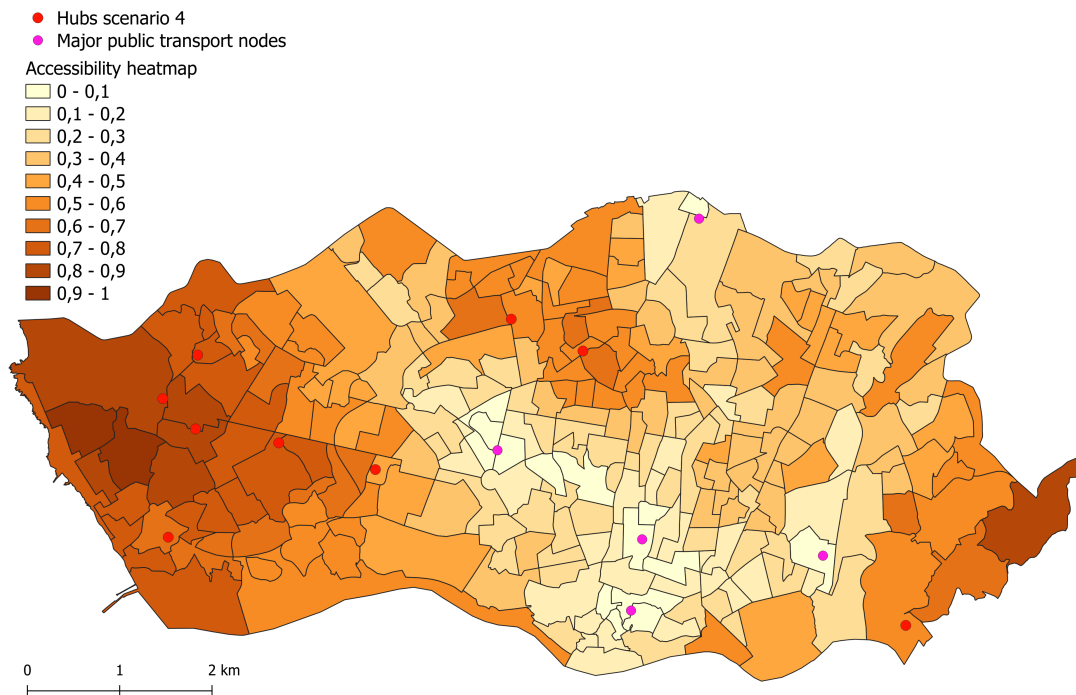


Figure 4.12: Scenario 4

transport option, and the accessibility value remained equal to the As-Is travel time. Therefore, the To-Be accessibility value for each section corresponds to the minimum travel time between the existing public transport alternative and the new multimodal alternative involving carsharing.

This scenario design makes it possible to compare the magnitude of accessibility improvements and the trade-offs between different candidate policies. The following section evaluates the impacts of these policy scenarios and associated trade-offs.

4.5 Impact assessment

The impact assessment was structured into four complementary analyses. First, accessibility improvements were mapped in order to visualise the spatial distribution of the benefits generated by each scenario. Second, descriptive statistics and boxplots were used to compare overall accessibility levels before and after the hubs' implementation. Third, cumulative improvement curves were constructed to evaluate whether the benefits were concentrated in the sections that each scenario intended to prioritise, namely the least accessible sections or those with higher "priority" scores. Finally, a trade-off analysis between accessibility gains and a simplified investment metric was conducted, enabling comparison of the policy scenarios from both performance and implementation-effort perspectives.

Together, these analyses make it possible to assess the impact of each scenario in terms of accessibility improvement, detailing where improvements occur, who benefits most, and how

these benefits compare with the relative investment required. This supports more comprehensive decision-making process on shared mobility services as a potential policy tool to improve first- and last-mile connectivity and promote more equity-oriented accessibility outcomes.

Accessibility: mapping the improvements

The first part of the impact assessment consisted of mapping the spatial distribution of accessibility improvements generated by each carsharing hub-location scenario. In the following maps, the statistical sections highlighted in red correspond to the areas where the To-Be accessibility value was lower than the As-Is accessibility value. In other words, these are the sections where the multimodal alternative involving carsharing reduced the travel time to the nearest major public transport node. The green labels displayed over each benefited section indicate the magnitude of the improvement, expressed in seconds. Sections not highlighted in red did not experience a reduction in travel time and therefore retained their original As-Is accessibility value.

This mapping approach allows policy-makers to immediately identify not only whether a scenario improves accessibility, but also where these improvements occur and how large they are. It also helps detect hub locations that may not generate relevant accessibility benefits for the surrounding areas, which is important from an investment and planning perspective.

Figure 4.13 presents the accessibility improvements obtained in Scenario 1, in which carsharing hubs were implemented in all public charging stations.

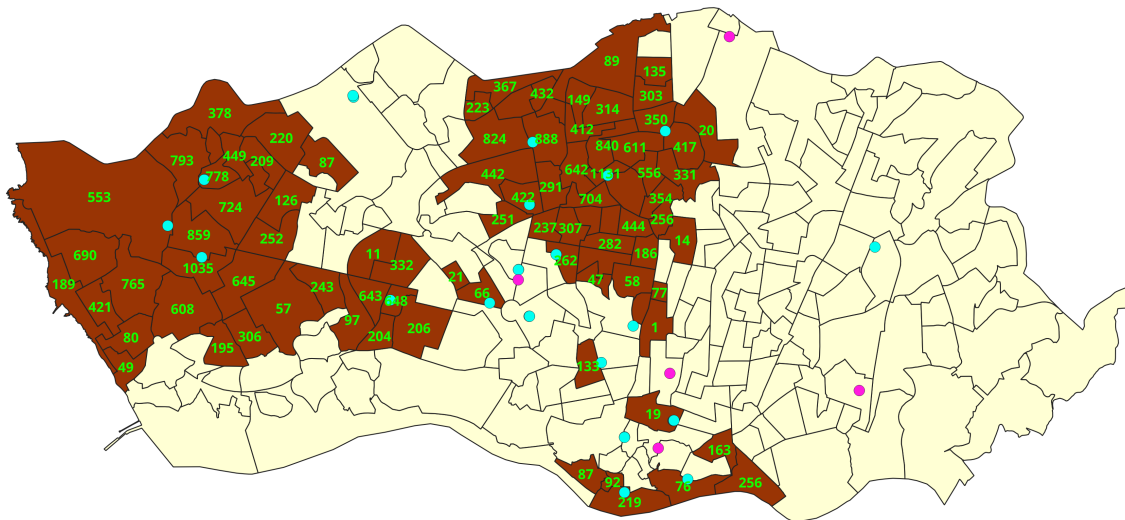


Figure 4.13: Accessibility improvement in scenario 1

The results show a broad spatial distribution of improvements, particularly in the western part of the municipality and in some northern and central areas. However, the map also shows that not all implemented hubs generated benefits in their surrounding sections. In particular, hubs located close to the major public transport nodes or near the metro line showed limited additional value, since residents in those areas can already reach the selected destinations efficiently using active modes (e.g., walking) or the existing public transport network. This finding is key to policy design

because it suggests that implementing carsharing hubs in these areas, besides being an investment that yields no accessibility gains, may also risk competing with active modes or conventional public transport rather than complementing them. In such cases, it may be worth exploring other shared mobility services, such as micromobility sharing, or improving the current public transport services. This first map also highlights the limitations of relying on existing public infrastructure for hub allocation, as no accessibility improvements are observed in the eastern part of the study area due to the lack of nearby potential hub locations.

Figure 4.14 shows the improvements obtained in Scenario 2, where 9 hubs were selected according to the accessibility heatmap, using only public charging stations.

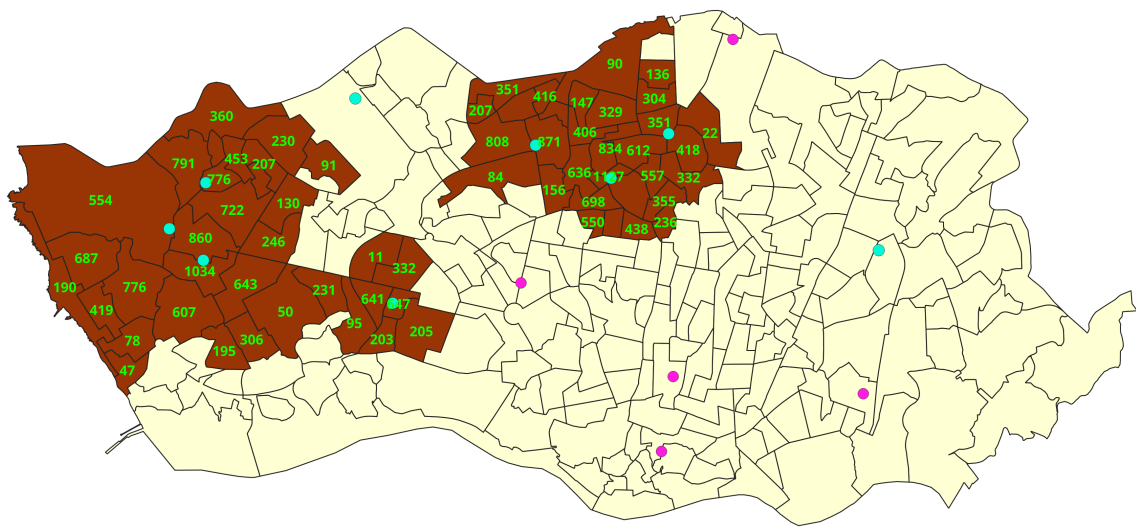


Figure 4.14: Accessibility improvement in scenario 2

The improvements are mainly concentrated in the western and north-western areas of Porto, which correspond to areas with poorer As-Is accessibility. However, the map reveals that 2 out of the 9 selected hubs did not generate accessibility improvements in nearby sections. This result can be explained, once again, by their proximity to metro infrastructure and by the exclusive use of public charging stations that constrained the spatial placement of hubs, preventing the scenario from fully addressing some of the most critical accessibility gaps where no suitable public charging station was available.

Figure 4.15 presents Scenario 3, which was based on the priority heatmap and used a combination of 5 public and 4 private charging stations. This scenario aimed to target areas with higher accessibility-related vulnerability, considering not only As-Is accessibility but also public transport frequency, income vulnerability, and car availability vulnerability.

The map shows improvements in the western part of the municipality, but also in some eastern areas that were not as strongly covered in Scenario 2. This reflects the use of private charging stations to address gaps in public infrastructure near high-priority sections. Nevertheless, the results also show that the inclusion of private stations does not automatically guarantee accessibility

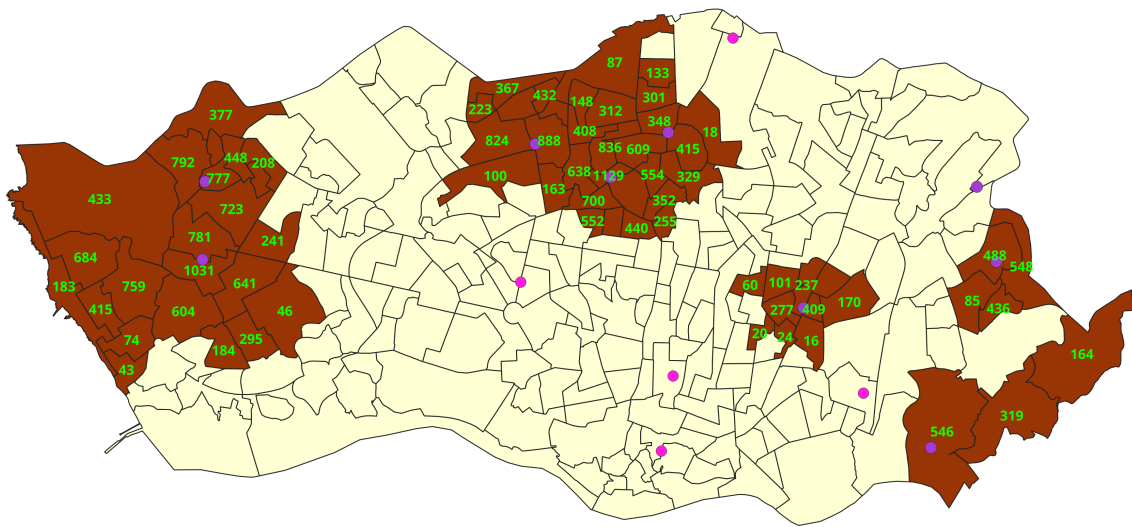


Figure 4.15: Accessibility improvement in scenario 3

improvements. Some hubs located in areas with nearby metro access or less favourable spatial positioning relative to section centroids generated limited benefits. This reinforces the importance of evaluating hub placement not only through priority criteria, but also through the actual travel-time impacts produced after implementation.

Figure 4.16 presents Scenario 4, in which 9 hubs were selected according to the accessibility heatmap, using a mix of 6 public and 3 private charging stations.

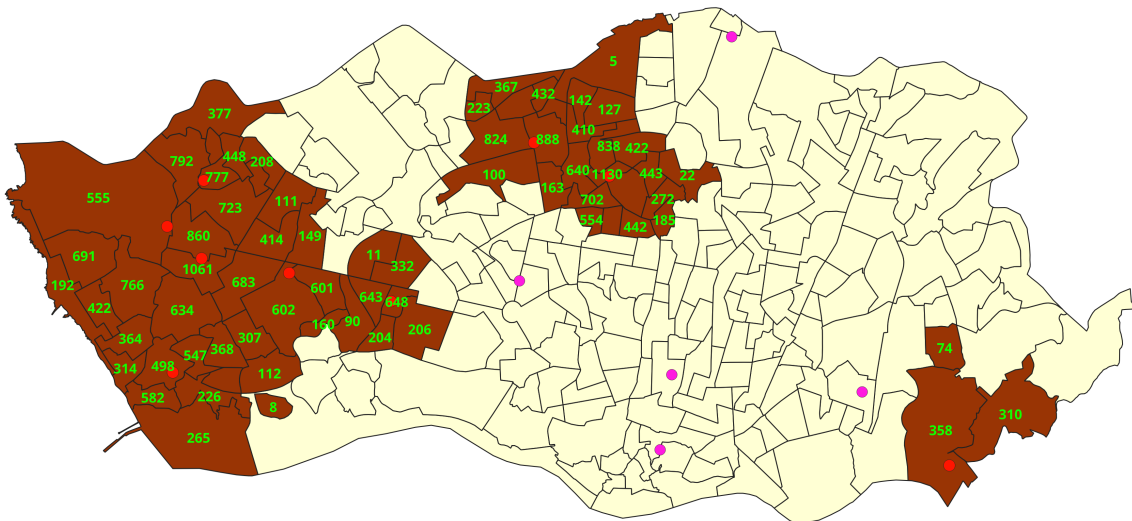


Figure 4.16: Accessibility improvement in scenario 4

The results show strong improvements in the western part of the municipality, where several sections are farther from the metro network and more dependent on bus services. Compared with Scenario 2, the inclusion of private charging stations allowed hubs to be located closer to areas with poorer accessibility, reducing some of the limitations caused by relying only on public charging infrastructure.

Overall, the improvement maps show that the spatial distribution of benefits is strongly influenced by the available candidates for hub location. Scenarios based only on public charging stations were limited by the spatial distribution of existing public infrastructure, while mixed public-private scenarios provided greater flexibility to target underserved areas. The maps also show that carsharing hubs are most effective when they complement gaps in the public transport network, particularly in areas farther from metro lines or major transport nodes.

Overall accessibility performance of the scenarios

The boxplot comparison found in Figure 4.17 provides an overview of the accessibility distribution under the As-Is situation and the four alternative carsharing policy scenarios. The results show a consistent downward shift in travel times across all scenarios, indicating that the introduction of carsharing hubs improves accessibility to major public transport nodes. Compared with the As-Is situation, all scenarios present lower median and average travel times, as well as a reduction in the upper range of the distribution. This suggests that the proposed interventions not only improve average accessibility but also reduce some of the most extreme accessibility disadvantages observed under the current public transport network.

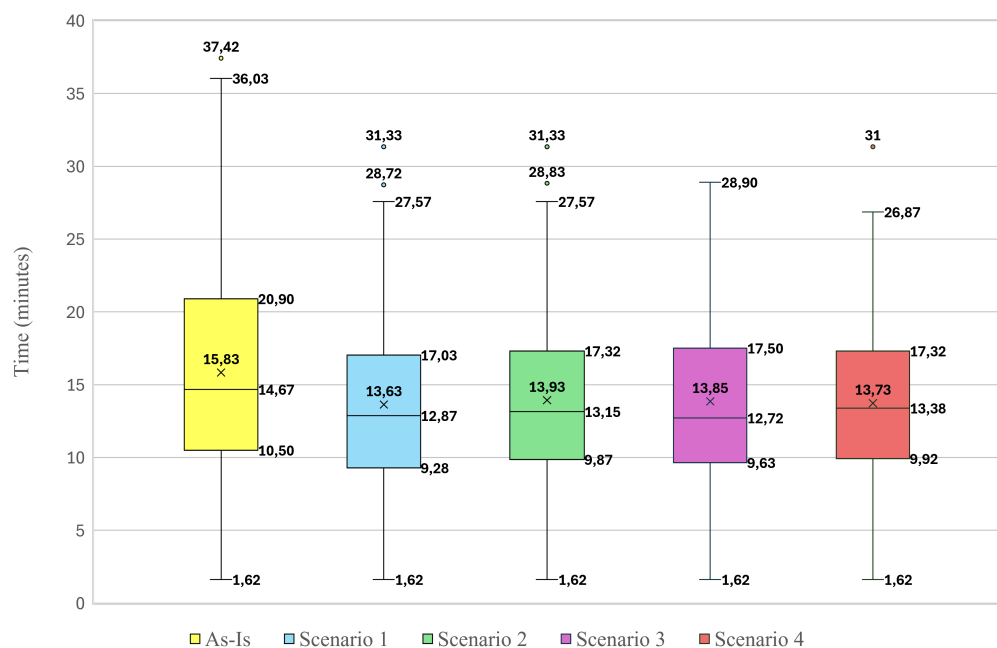


Figure 4.17: Distribution of travel times to the nearest major public transport node under the As-Is situation and alternative policy scenarios

In the As-Is situation, travel times are more dispersed and reach the highest maximum value among all scenarios. The average travel time is 15.83 minutes, with a median of 14.67 minutes, while the maximum observed travel time reaches 37.42 minutes. These values reveal the existence of statistical sections with substantially poorer accessibility to major public transport nodes under the current transport system.

Scenario 1, in which carsharing hubs are located at all public charging stations, produces the strongest overall accessibility improvement. The boxplot shows a clear reduction in both the central tendency and upper range of travel times. The average travel time decreases to 13.63 minutes, corresponding to an average reduction of 2.20 minutes, or 13.92%, compared with the As-Is situation. This scenario benefits 89 statistical sections, representing 36.3% of the study area. This result is expected, since Scenario 1 corresponds to the most extensive deployment among the scenarios based exclusively on public charging infrastructure.

Scenario 2, which locates hubs at public charging stations selected according to the accessibility heatmap, also reduces travel times, although with a more limited spatial impact. The average travel time decreases to 13.93 minutes, corresponding to an average reduction of 1.91 minutes, or 12.03%. In total, 65 statistical sections experience an improvement, representing 26.5% of the study area. This reflects the more selective nature of the intervention and the constraints imposed by relying only on public charging points located in areas identified as having lower accessibility.

Scenario 3, based on the priority heatmap and using a mix of public and private charging stations, presents an average travel time of 13.85 minutes, corresponding to an average reduction of 1.98 minutes, or 12.53%, compared with the As-Is situation. This scenario benefits 71 statistical sections, representing 29.22% of the study area. Although it does not produce the lowest average travel time, the boxplot indicates a relevant reduction in the upper range of the distribution, with the lowest maximum travel time among the tested scenarios. This suggests that the priority-based approach may be particularly effective in reducing the most extreme accessibility disadvantages, while also incorporating socioeconomic and transport-related vulnerability criteria.

Scenario 4, in which hubs are located according to the accessibility heatmap using a mix of public and private charging stations, presents the second-best performance in terms of average travel time. The average decreases to 13.73 minutes, corresponding to a reduction of 2.11 minutes, or 13.31%, compared with the As-Is situation. As in Scenario 3, 71 statistical sections experience accessibility improvements. This result suggests that expanding the set of candidate locations to include private charging stations can improve the effectiveness of accessibility-based planning, particularly by increasing spatial coverage in areas where public charging infrastructure is limited.

Overall, the boxplot analysis highlights that carsharing hubs can contribute to reducing travel times to major public transport nodes and improve first- and last-mile connectivity, but suggests a trade-off between spatial coverage, accessibility efficiency, and equity-oriented prioritisation. Scenario 1 achieves the largest average accessibility gains, but it does so through the most extensive use of hub allocation. Scenario 2 is more selective but produces more limited improvements. Scenario 3 does not maximise average accessibility gains, but it introduces an equity-oriented rationale by prioritising areas according to multiple vulnerability criteria. Scenario 4 combines the accessibility-based logic with a broader set of candidate locations, achieving strong average improvements and wider spatial coverage than the public-only accessibility scenario.

Accessibility improvement distribution

To complement the analysis of accessibility improvements, the distribution of benefits across the statistical sections was further examined. Two cumulative improvement curves were constructed to assess whether each scenario effectively targeted the sections it was designed to prioritise.

The first curve (Figure 4.18) orders statistical sections according to the priority indicator, from the highest to the lowest priority. This allows the evaluation of whether accessibility improvements are concentrated in the areas identified as most vulnerable according to the composite priority indicator. The second curve (Figure 4.19) orders statistical sections according to their initial accessibility level, from the lowest to the highest accessibility. This makes it possible to assess whether the scenarios based on the accessibility heatmap effectively benefited the sections that were initially less accessible. In both graphs, the y-axis represents cumulative accessibility improvements, while the dashed vertical line marks the first 30% of sections, enabling a comparison of how much improvement is accumulated among the most critical sections according to each ordering criterion.

When sections are ordered by priority, compared to the other scenarios, Scenario 3 shows a stronger initial increase in cumulative accessibility improvements, particularly within the first 30% of sections. This result is consistent with the logic used to construct this scenario, since hub locations were selected based on the priority heatmap, which combines accessibility, public transport frequency, income level, and car availability. Therefore, the curve suggests that Scenario 3 is relatively effective in directing accessibility gains towards the sections identified as having higher mobility-related vulnerability.

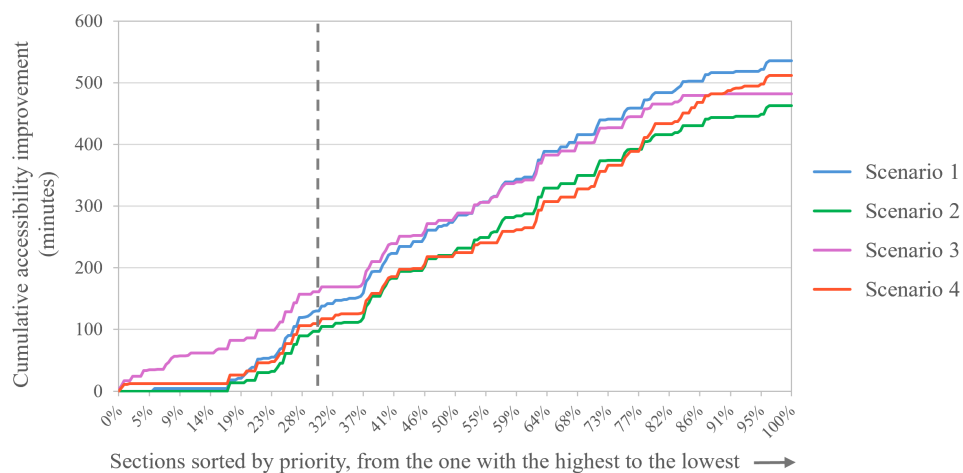


Figure 4.18: Accessibility distribution analysis sorted by priority

Scenario 1 also accumulates substantial improvements, reflecting its extensive deployment strategy, in which hubs are located at all public charging stations. However, its performance is mainly explained by broader spatial coverage rather than by an explicit equity-oriented prioritisation criterion. Scenario 2 presents a more limited accumulation of improvements among high-

priority sections, suggesting that the use of public charging stations only may constrain the ability to benefit the most vulnerable areas. Scenario 4 also performs well, showing that the inclusion of private charging stations expands the set of feasible locations and improves the capacity to reach sections with higher priority.

When sections are ordered according to current accessibility level, Scenario 4 presents the strongest initial accumulation of improvements among the least accessible sections. This indicates that the accessibility-based strategy, combined with both public and private charging stations, which enabled a more flexible hub allocation, was particularly effective in targeting areas with poorer initial accessibility.

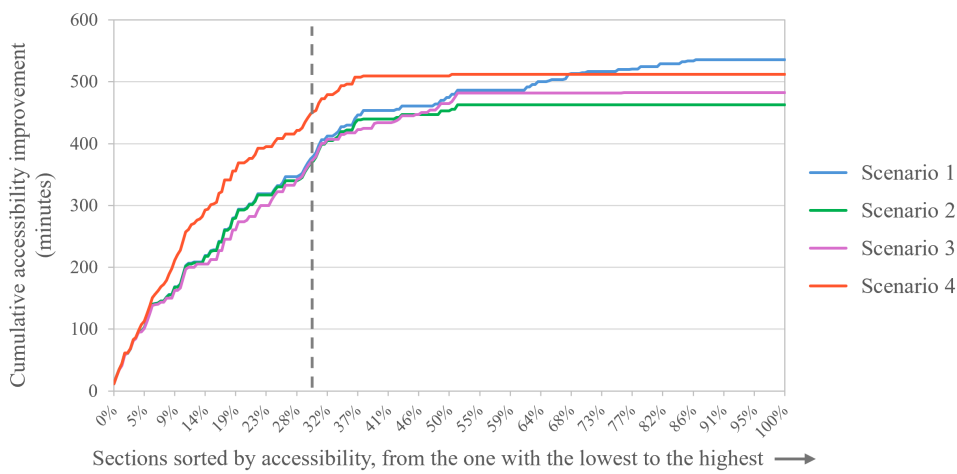


Figure 4.19: Accessibility distribution analysis sorted by accessibility

In this sense, the cumulative improvement curves confirm that the heatmap-based approach for selecting shared mobility services locations was effective in producing results aligned with the intended policy objective.

Trade-off between accessibility and investment

In addition to accessibility gains, policy-makers must also consider the investment required to implement each candidate policy. To complement the accessibility assessment, a trade-off analysis between accessibility improvements and implementation effort was conducted. From a policy-making perspective, the scenario that achieves the greatest improvement in accessibility may not be the most desirable if it requires substantially higher investment. Since actual implementation costs were unavailable, a simplified investment metric was defined to compare the relative implementation effort for each scenario. It should be noted that the investment metric is expressed in theoretical monetary units. This approach was adopted because the analysis aims to compare the relative investment requirements of public and private charging stations, rather than to estimate their absolute implementation costs.

This metric was based on the number and type of charging stations used as candidate locations for carsharing hubs. Public charging stations were assumed to require a lower implementation effort, as they correspond to publicly available infrastructure. Private charging stations were assumed to require greater implementation effort, since their use would likely require additional agreements with private operators or infrastructure adaptations. To account for uncertainty in these assumptions, two cost settings were tested. In the first one, on Figure 4.20, a hub located at a public charging station was assigned a cost of 1 monetary unit, while a hub located at a private charging station was assigned a cost of 3 units. In the second one, on Figure 4.21, the public station cost remained 1 unit, while the private station cost was increased to 5 units.

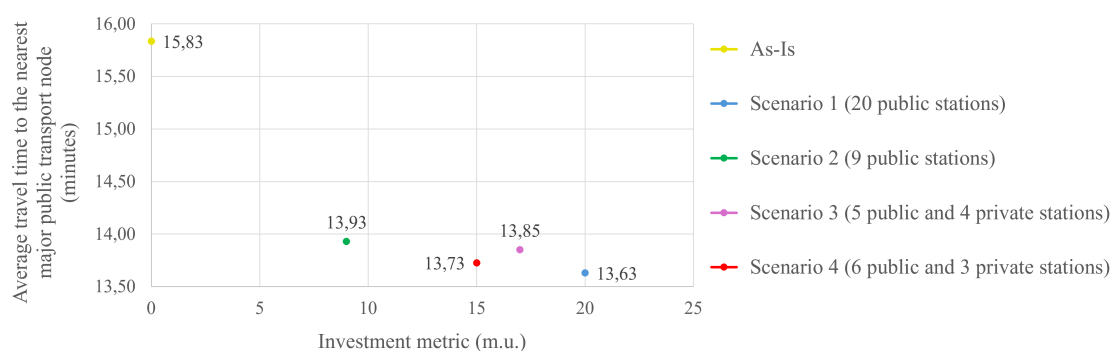


Figure 4.20: Trade-off between accessibility and investment for a relative cost difference between private and public station locations of 1:3

Under the first cost assumption, as expected, Scenario 1 achieves the lowest average travel time, 13.63 minutes, but requires the largest implementation effort associated with the 20 public charging stations. Scenario 2 has the lowest investment requirement, with only 9 public stations, but presents the highest average travel time among the alternative policy scenarios, 13.93 minutes. Scenario 4 appears as a strong compromise, reaching an average travel time of 13.73 minutes with fewer hubs than Scenario 1 by combining 6 public and 3 private stations. Scenario 3, being the second most expensive policy scenario, with 5 public and 4 private stations, achieves an average travel time of 13.85 minutes, but its interpretation should also consider its equity-oriented objective, as this extra cost was required in order to address the sections highlighted by the priority heatmap.

When the assumed cost of private charging stations increases from 3 to 5 monetary units, Scenarios 3 and 4 become less favourable from an investment-efficiency perspective, particularly Scenario 3 due to its greater reliance on private stations. Scenarios 1 and 2 remain unchanged, as they only use public charging infrastructure. This sensitivity test shows that the attractiveness of mixed public-private strategies depends strongly on the additional implementation effort associated with private infrastructure.

Overall, the trade-off analysis shows that the preferred scenario depends on the policy objective. Scenario 1 is preferable if the main goal is to minimize average travel time. Scenario 2 is

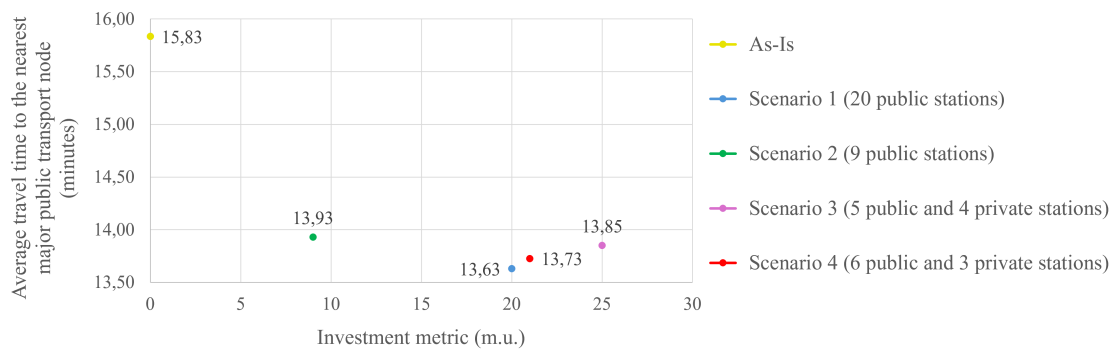


Figure 4.21: Trade-off between accessibility and investment for a relative cost difference between private and public station locations of 1:5

preferable if the goal is to minimize investment. Scenario 4 provides the most balanced compromise between accessibility gains and implementation effort under the tested assumptions. Scenario 3, despite not being the best in terms of average travel time or investment efficiency, remains relevant as an equity-oriented alternative designed to target areas with higher vulnerability.

It is important to note that this trade-off analysis provides only an aggregate comparison between scenarios, based on average travel time and a simplified investment metric. While this perspective is useful for comparing the overall performance and relative implementation effort of each policy option, it does not capture the spatial distribution of benefits or the specific areas where improvements occur. For this reason, this aggregate indicator should be complemented with the spatial analyses presented in the previous sections, including the improvement maps and cumulative improvement curves. Together, these outputs provide policy-makers with a more complete basis for decision-making, allowing them to consider not only which scenario performs better on average, but also where benefits are generated, which areas are prioritized, and whether the selected policy is aligned with the intended equity objectives. This analysis reinforces the role of the proposed methodology as a decision-support tool, allowing policy-makers to compare policy scenarios under different assumptions and to make explicit the trade-offs between accessibility improvements, equity-oriented prioritization, spatial coverage, and investment effort.

Chapter 5

Conclusion

This thesis contributes to the discussion on how shared mobility services can be planned and implemented as part of more equitable urban transport systems. The first contribution lies in the literature review, which brings together three bodies of research that are often discussed separately: accessibility and equity in urban mobility, the opportunities and risks associated with shared mobility services, and the important role of transport policy-making. By doing so, it offers a conceptual basis for understanding how shared mobility services can be planned and implemented to support more equitable urban mobility outcomes.

The second contribution is the development of a GIS-based methodological framework to support policy-makers and transport planners in locating shared mobility services from a vertical equity perspective. By applying this methodology to the case study of Porto, the thesis demonstrates how data-driven spatial analysis can be used to characterize the current mobility conditions of the public transport network, identify priority areas for intervention, simulate alternative policy scenarios, and assess their impacts. The comparison between scenarios makes it possible to evaluate accessibility gains, but also the spatial distribution of improvements and the trade-offs between accessibility efficiency, equity-oriented prioritization, and investment effort.

In addition to these contributions, Appendix B provides a complementary reflection on how the work developed in this thesis relates to the United Nations Sustainable Development Goals. This analysis highlights the connection between the proposed methodology and SDGs 9, 10, and 11, particularly regarding sustainable infrastructure, reduced inequalities, and more inclusive and integrated urban mobility planning. By identifying the relevant goals, targets, contributions, and potential performance indicators, the appendix reinforces the dissertation's broader societal relevance and situates the proposed decision-support framework within the wider agenda of sustainable development.

Overall, the proposed framework should be understood as a decision-support tool rather than as a model that produces a single optimal solution. Its main value lies in enabling policy-makers to test different assumptions, criteria, and implementation policies, while making explicit the consequences of each decision. In this sense, the methodology contributes to a more equity-aware

planning process, supporting the use of shared mobility services as a potential instrument to reduce accessibility-related vulnerabilities and complement existing public transport networks.

Limitations and future research

Although the proposed methodology provides a useful framework for locating shared mobility services from an equity-oriented perspective, some limitations and alternative uses of this framework should be acknowledged.

First, the accessibility analysis was based on access to a selected set of major public transport nodes. This choice was consistent with the objective of assessing carsharing hubs as a first- and last-mile solution capable of improving connections to the existing public transport network. However, other destination types could also be considered in future applications, such as schools, healthcare facilities, employment centers, or public services.

Second, this study focused specifically on electric carsharing hubs. Nevertheless, the same methodological framework could be adapted to other forms of shared mobility. For example, bikesharing and shared micromobility may be particularly relevant for shorter trips and younger populations, while carsharing may be more appropriate for longer first- and last-mile connections or areas with weaker public transport supply. Future research could therefore compare different shared mobility services and assess which solutions are more appropriate for different mobility needs and urban contexts.

Third, the criteria used to construct the priority heatmap were accessibility, public transport frequency, income level, and car availability. These indicators were selected to capture relevant dimensions of mobility-related vulnerability. However, other indicators could also be incorporated depending on policy objectives and data availability, such as age structure, disability, employment status, student population, population density, or the spatial distribution of specific essential services. The methodology is intentionally flexible, and future applications could adapt the criteria to different planning priorities and local contexts.

In terms of limitations, the accessibility measure used in this study has some methodological limitations. Accessibility was measured as the minimum travel time from each statistical section to the nearest major public transport node. Although this measure is simple, interpretable, and useful for policy communication, it does not capture all dimensions of accessibility. In particular, it does not fully account for the destinations' attractiveness. Future work could explore more robust accessibility measures, such as gravity-based measures that incorporate destination attractiveness. Moreover, the QGIS plugin used to estimate travel times did not allow full control over certain assumptions underlying the calculations, such as transfer times between transport modes or waiting times. In the future, it would be interesting to use more robust methods to calculate travel times between the origin and destinations, with greater control over the assumptions made.

A further limitation concerns the aggregation of the spatial data. The study was conducted at the statistical section level, which was the most appropriate spatial unit given the available data. However, some statistical sections include non-residential areas, such as large parks, infrastructure areas, or other urban spaces with limited population. Since population density was not included

as a prioritization criterion, some areas may appear relevant in the spatial analysis even if they contain a limited residential population. Future research could address this limitation by using more disaggregated spatial data, such as statistical subsections, allowing residential areas to be distinguished more clearly from non-residential land uses.

In addition, the To-Be scenarios assume that individuals choose the option with the lowest travel time. If the public transport alternative is faster, users are assumed to maintain their existing trip; if the carsharing alternative is faster, they are assumed to use carsharing. This simplifying assumption is useful for estimating potential accessibility gains, but it does not fully represent real travel behaviour. In practice, mode choice also depends on factors such as cost, convenience, availability, perceived safety, and personal preferences. Future research could incorporate more realistic behavioural assumptions, for example through discrete choice models.

Finally, the implementation of infrastructure alone is not sufficient to ensure equitable mobility outcomes. Shared mobility services must also be affordable, inclusive, easy to use, and accessible to people with low levels of digital literacy or limited access to digital payment systems. Otherwise, there is a risk that the potential benefits identified in the analysis do not reach the population groups that need them most. For this reason, infrastructure planning should be complemented by policies related to pricing, service regulation, user inclusion, local engagement, and accessibility for vulnerable groups, such as older adults, people with reduced mobility, and low-income users.

Overall, these limitations do not undermine the relevance of the proposed methodology. Instead, they highlight opportunities to further develop and refine the framework in future research. The main contribution of this dissertation lies in demonstrating how data-driven analysis can support more interpretable and equity-aware decisions regarding the location of shared mobility services. By combining accessibility indicators, socioeconomic and demographic criteria, GIS-based heatmaps, and scenario comparison, the proposed framework provides policy-makers and transport planners with a practical tool to identify priority intervention areas and assess the trade-offs associated with different implementation strategies. In this way, the thesis contributes not only to the planning of shared mobility services as complements to public transport, but also to broader discussions on how urban mobility systems can become more accessible, inclusive, and socially sustainable.

Bibliography

- Alam, B. M., Thompson, G. L., and Brown, J. R. (2010). Estimating transit accessibility with an alternative method: Evidence from broward county, florida. *Transportation Research Record: Journal of the Transportation Research Board*, 2144:62–71.
- Angelopoulos, A., Gavalas, D., Konstantopoulos, C., Kypriadis, D., and Pantziou, G. (2018). Incentivized vehicle relocation in vehicle sharing systems. *Transportation Research Part C: Emerging Technologies*, 97:175–193.
- Bian, Z., Liu, X., and Bai, Y. (2020). Mechanism design for on-demand first-mile ridesharing. *Transportation Research Part B: Methodological*, 138:77–117.
- Cheng, Y., Wang, J., and Wang, Y. (2021). A user-based bike rebalancing strategy for free-floating bike sharing systems: A bidding model. *Transportation Research Part E: Logistics and Transportation Review*, 154:102438.
- Coenegrachts, E., Vanelslander, T., Verhetsel, A., and Beckers, J. (2024). Analyzing shared mobility markets in europe: A comparative analysis of shared mobility schemes across 311 european cities. *Journal of Transport Geography*, 118:103918.
- Cohen, A. P. and Shaheen, S. A. (2016). *Planning for shared mobility*. American Planning Association. ISBN: 9781611901863.
- Cohen, B. and Kietzmann, J. (2014). Ride on! mobility business models for the sharing economy. *Organization & Environment*, 27:279–296.
- de Jong, G., Daly, A., Pieters, M., and van der Hoorn, T. (2007). The logsum as an evaluation measure: Review of the literature and new results. *Transportation Research Part A: Policy and Practice*, 41:874–889.
- Delafontaine, M., Neutens, T., Schwanen, T., and de Weghe, N. V. (2011). The impact of opening hours on the equity of individual space–time accessibility. *Computers, Environment and Urban Systems*, 35:276–288.
- Delbosc, A. and Currie, G. (2011). Using lorenz curves to assess public transport equity. *Journal of Transport Geography*, 19:1252–1259.
- Diana, M. and Chicco, A. (2022). The spatial reconfiguration of parking demand due to car sharing diffusion: a simulated scenario for the cities of milan and turin (italy). *Journal of Transport Geography*, 98:103276.
- Direção-Geral de Energia e Geologia (2025). Plano nacional de energia e clima 2030. URL: <https://www.dgeg.gov.pt/pt/areas-transversais/relacoes-institucionais-e-de-mercado/politica-energetica/planos-nacionais-para-o-setor-energetico/> Accessed on 28/03/2026.

- European Commission (2019). The european green deal. URL:https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en Accessed on 28/03/2026.
- Expresso, J. (2026). A palavra-passe em 2026 é integração. URL:<https://expresso.pt/podcasts/mobi-boom/2026-03-22-a-palavrapasse-em-2026-e-integracao.-nao-e-aceitavel-uma-pessoa-ter-cinco-apps-para-andar-de-transportes-publicos-e-desmotivador-afa1831d> Accessed on 28/03/2026.
- Felson, M. and Spaeth, J. L. (1978). Community structure and collaborative consumption: A routine activity approach. *American Behavioral Scientist*, 21:614–624.
- Frank, L., Bradley, M., Kavage, S., Chapman, J., and Lawton, T. K. (2007). Urban form, travel time, and cost relationships with tour complexity and mode choice. *Transportation*, 35:37–54.
- Furuhata, M., Dessouky, M., Ordóñez, F., Brunet, M.-E., Wang, X., and Koenig, S. (2013). Ridesharing: The state-of-the-art and future directions. *Transportation Research Part B: Methodological*, 57:28–46.
- Gao, J. and Li, S. (2024). Synergizing shared micromobility and public transit towards an equitable multimodal transportation network. *Transportation Research Part A: Policy and Practice*, 189:104225.
- Geurs, K. T. and van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography*, 12:127–140.
- GTFS (2026). What is gtfs? URL:<https://gtfs.org/getting-started/what-is-gtfs/> Accessed on 02/05/2026.
- Guan, R., Zhou, Y., and Yang, H. (2025). Promoting shared mobility through incentives: Review and prospects. *Transportation Research Part C: Emerging Technologies*, 180:105355.
- Guzman, L. A. and Oviedo, D. (2018). Accessibility, affordability and equity: Assessing ‘pro-poor’ public transport subsidies in bogotá. *Transport Policy*, 68:37–51.
- Hansen, W. G. (1959). How accessibility shapes land use. *Journal of the American Institute of Planners*, 25:73–76.
- Hensher, D. A., Ho, C. Q., and Reck, D. J. (2021). Mobility as a service and private car use: Evidence from the sydney maas trial. *Transportation Research Part A: Policy and Practice*, 145:17–33.
- Herszenhut, D., Pereira, R. H., da Silva Portugal, L., and de Sousa Oliveira, M. H. (2022). The impact of transit monetary costs on transport inequality. *Journal of Transport Geography*, 99:103309.
- Horjus, J., Gkiotsalitis, K., Nijenstein, S., and Geurs, K. (2022). Integration of shared transport at a public transport stop: mode choice intentions of different user segments at a mobility hub. *Journal of Urban Mobility*, 2:100026.
- Howlett, M. and Cashore, B. (2009). The dependent variable problem in the study of policy change: Understanding policy change as a methodological problem. *Journal of Comparative Policy Analysis: Research and Practice*, 11:33–46.

- Instituto Nacional de Estatística (2018). Mobilidade e funcionalidade do território nas Áreas metropolitanas do porto e de lisboa 2017. Technical report, Instituto Nacional de Estatística. URL:https://www.tmlmobilidade.pt/wp-content/uploads/2022/06/IMOB_2017A.pdf Accessed on 03/05/2026.
- Instituto Nacional de Estatística (2026). Census 2021 geospatial data. URL:<https://mapas.ine.pt/download/index2021.phtml> Accessed on 31/04/2026.
- Jin, T., Cheng, L., Wang, K., Cao, J., Huang, H., and Witlox, F. (2022). Examining equity in accessibility to multi-tier healthcare services across different income households using estimated travel time. *Transport Policy*, 121:1–13.
- Junyent, I. A., Casanovas, M. M., Roukouni, A., Sanz, J. M., Blanch, E. R., and de Almeida Correia, G. H. (2024). Planning shared mobility hubs in european cities: A methodological framework using mcda and gis applied to barcelona. *Sustainable Cities and Society*, 106:105377.
- Järv, O., Tenkanen, H., Salonen, M., Ahas, R., and Toivonen, T. (2018). Dynamic cities: Location-based accessibility modelling as a function of time. *Applied Geography*, 95:101–110.
- Kapuku, C., Kho, S.-Y., Kim, D.-K., and Cho, S.-H. (2021). Assessing and predicting mobility improvement of integrating bike-sharing into multimodal public transport systems. *Transportation Research Record: Journal of the Transportation Research Board*, 2675:204–213.
- Karner, A., Pereira, R. H. M., and Farber, S. (2025). Advances and pitfalls in measuring transportation equity. *Transportation*, 52:1399–1427.
- Lazarus, J., Pourquier, J. C., Feng, F., Hammel, H., and Shaheen, S. (2020). Micromobility evolution and expansion: Understanding how docked and dockless bikesharing models complement and compete – a case study of san francisco. *Journal of Transport Geography*, 84:102620.
- Leat, S., Cronley, C., Hyun, K. K., and Naz, F. (2022). Examining the feasibility of shared mobility programs for reducing transportation inequities: Perspectives from the front-line. *Journal of Poverty*, 26:622–640.
- Litman, T. (2025). Evaluating transportation equity: Guidance for incorporating distributional impacts in transportation planning. Technical report, Victoria Transport Policy Institute.
- Lloret-Batlle, R., Masoud, N., and Nam, D. (2017). Peer-to-peer ridesharing with ride-back on high-occupancy-vehicle lanes: Toward a practical alternative mode for daily commuting. *Transportation Research Record: Journal of the Transportation Research Board*, 2668:21–28.
- Lovett, A., Haynes, R., Sünnerberg, G., and Gale, S. (2002). Car travel time and accessibility by bus to general practitioner services: a study using patient registers and gis. *Social Science & Medicine*, 55:97–111.
- Lucas, K., van Wee, B., and Maat, K. (2016). A method to evaluate equitable accessibility: combining ethical theories and accessibility-based approaches. *Transportation*, 43:473–490.
- Marsden, G. and Reardon, L. (2017). Questions of governance: Rethinking the study of transportation policy. *Transportation Research Part A: Policy and Practice*, 101:238–251.
- Martens, K., Golub, A., and Robinson, G. (2012). A justice-theoretic approach to the distribution of transportation benefits: Implications for transportation planning practice in the united states. *Transportation Research Part A: Policy and Practice*, 46:684–695.

- Martinez, L. M., Pritchard, J. P., and Crist, P. (2024). Shared mobility's role in sustainable mobility: Past, present, and future. *Annual Review of Environment and Resources*, 49:191–222.
- Mavoa, S., Witten, K., McCreanor, T., and O'Sullivan, D. (2012). Gis based destination accessibility via public transit and walking in auckland, new zealand. *Journal of Transport Geography*, 20:15–22.
- MOBIE (2026). Charging stations in the city of porto. URL:<https://www.mobie.pt/en/chargevehicle/findachargingstation> Accessed on 02/05/2026.
- Niemeier, D. A. (1997). Accessibility: an evaluation using consumer welfare. *Transportation*, 24:377–396.
- Palma, J. G. (2011). Homogeneous middles vs. heterogeneous tails, and the end of the 'inverted-u': It's all about the share of the rich. *Development and Change*, 42:87–153.
- Porto Digital (2026a). Metro do porto schedules, stops and routes. URL:<https://opendata.porto.digital/dataset/horarios-paragens-e-rotas-em-formato-gtfs> Accessed on 31/04/2026.
- Porto Digital (2026b). Public charging stations in the city of porto. URL:<https://opendata.porto.digital/dataset/p-publico-0145> Accessed on 02/05/2026.
- Porto Digital (2026c). Stop schedules, stops and routes. URL:<https://opendata.porto.digital/dataset/horarios-paragens-e-rotas-em-formato-gtfs-stop> Accessed on 31/04/2026.
- Pritchard, J. P., Tomasiello, D. B., Giannotti, M., and Geurs, K. (2019). Potential impacts of bike-and-ride on job accessibility and spatial equity in são paulo, brazil. *Transportation Research Part A: Policy and Practice*, 121:386–400.
- QGIS (2026). Qgis software. URL:<https://www.qgis.org/> Accessed on 30/04/2026.
- Ramjerdi, F. (2006). Equity measures and their performance in transportation. *Transportation Research Record: Journal of the Transportation Research Board*, 1983:67–74.
- Richter, H. and Slowinski, P. R. (2019). The data sharing economy: On the emergence of new intermediaries. *IIC - International Review of Intellectual Property and Competition Law*, 50:4–29.
- Secretaria-Geral do Ambiente (2025). A política de transportes em portugal e os objetivos climáticos, perspetivas para o futuro. URL: <https://www.sgambiente.gov.pt/wp-content/uploads/2025/03/A-Politica-de-Transportes-em-Portugal-e-os-Objetivos-Climaticos.pdf> Accessed on 28/03/2026.
- Shafiq, M., Lobo, A., and Couto, A. (2024). Equity of access to rail services by complementary motorized and active modes. *Journal of Transport Geography*, 121:104007.
- Shaheen, S., Bell, C., Cohen, A., and Yelchuru, B. (2017). Travel behavior: Shared mobility and transportation equity. Technical report, Fed. Highw. Adm., Dep. Transp.
- Shaheen, S., Chan, N., Bansal, A., and Cohen, A. (2015). Shared mobility: A sustainability & technologies workshop: Definitions, industry developments, and early understanding. Technical report, UC Berkeley: Transportation Sustainability Research Center.

- Song, C., Monteil, J., Ygnace, J.-L., and Rey, D. (2021). Incentives for ridesharing: A case study of welfare and traffic congestion. *Journal of Advanced Transportation*, 2021:1–15.
- Sovacool, B. K., Daniels, C., and AbdulRafiu, A. (2022). Transitioning to electrified, automated and shared mobility in an african context: A comparative review of johannesburg, kigali, lagos and nairobi. *Journal of Transport Geography*, 98:103256.
- Stokkink, P. and Geroliminis, N. (2021). Predictive user-based relocation through incentives in one-way car-sharing systems. *Transportation Research Part B: Methodological*, 149:230–249.
- Tao, S., Cheng, L., Corcoran, J., and Shaheen, S. (2026). Multimodal public transport, travel behaviour, and social equity. *Travel Behaviour and Society*, 43:101237.
- Thomopoulos, N., Grant-Muller, S., and Tight, M. R. (2009). Incorporating equity considerations in transport infrastructure evaluation: Current practice and a proposed methodology. *Evaluation and Program Planning*, 32:351–359.
- TravelTime (2026). Travelttime qgis plugin for calculating travel times. URL:<https://travelttime.com/> Accessed on 05/05/2026.
- Tsavachidis, M. and Petit, Y. L. (2022). Re-shaping urban mobility – key to europe’s green transition. *Journal of Urban Mobility*, 2:100014.
- Tuffour, J. P. (2022). Contested mobility interactions: Characterizing the influence of ride-sharing services on the adoption and use of public transit system. *Case Studies on Transport Policy*, 10:2229–2243.
- UNECE (2020). Unece provides recommendations to support car sharing and carpooling in central asia’s green mobility shift. URL: <https://unece.org/circular-economy/press/unece-provides-recommendations-support-car-sharing-and-carpooling-central> Accessed on 30/03/2026.
- van Wee, B. (2016). Accessible accessibility research challenges. *Journal of Transport Geography*, 51:9–16.
- van Wee, B. and Mouter, N. (2021). Evaluating transport equity. *Advances in Transport Policy and Planning*, 7:103–126.
- Vine, S. L. and Polak, J. (2015). Introduction to special issue: new directions in shared-mobility research. *Transportation*, 42:407–411.
- Vélez, A. M. A. (2024). Environmental impacts of shared mobility: a systematic literature review of life-cycle assessments focusing on car sharing, carpooling, bikesharing, scooters and moped sharing. *Transport Reviews*, 44:634–658.
- Wang, H. and Yang, H. (2019). Ridesourcing systems: A framework and review. *Transportation Research Part B: Methodological*, 129:122–155.
- Wang, L., Li, W., Weng, J., Zhang, D., and Ma, W. (2023). Do low-carbon rewards incentivize people to ridesplitting? evidence from structural analysis. *Transportation*, 50:2077–2109.
- Wee, B. V., Wee, B. V., and Geurs, K. (2011). Discussing equity and social exclusion in accessibility evaluations. *European Journal of Transport and Infrastructure Research*.

- Xu, M., Di, Y., Zhu, Z., Yang, H., and Chen, X. (2022). Designing van-based mobile battery swapping and rebalancing services for dockless ebike-sharing systems based on the dueling double deep q-network. *Transportation Research Part C: Emerging Technologies*, 138:103620.
- Zhang, Q., Liu, Y., and Fan, Z.-P. (2023). Short-term subsidy strategy for new users of ride-hailing platform with user base. *Computers & Industrial Engineering*, 179:109177.
- Zhu, J., Xie, N., Cai, Z., Tang, W., and Chen, X. M. (2023). A comprehensive review of shared mobility for sustainable transportation systems. *International Journal of Sustainable Transportation*, 17:527–551.
- Zuniga-Garcia, N., Gurumurthy, K. M., Yahia, C. N., Kockelman, K. M., and Machemehl, R. B. (2022). Integrating shared mobility services with public transit in areas of low demand. *Journal of Public Transportation*, 24:100032.

Appendix A

Sensitivity analysis results

Figures A.1 to A.12 present the remaining heatmaps obtained from the sensitivity analysis. These figures allow a visual comparison of the alternative weighting schemes and show how changes in the criteria weights influence the spatial distribution of priority areas.

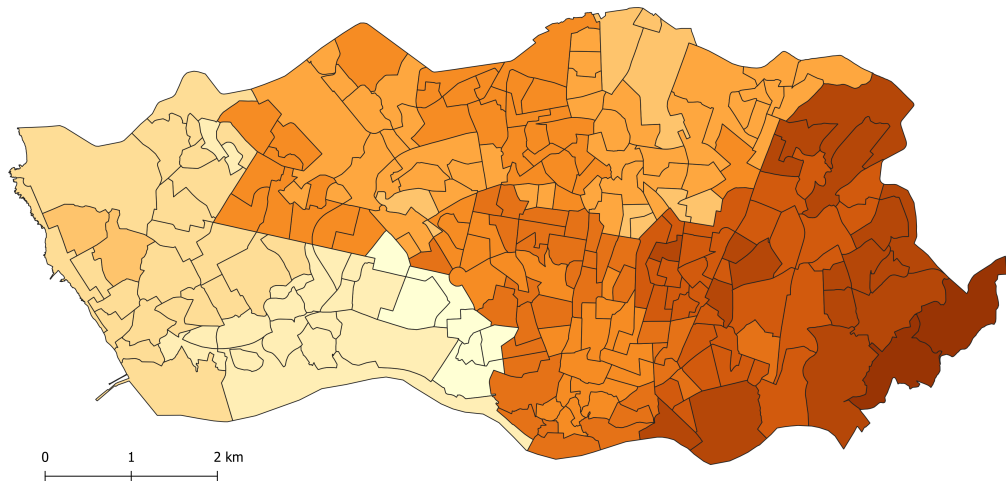


Figure A.1: Alternative 3: $\text{priority} = 0.3A + 0.1PTF + 0.5IV + 0.1CAV$

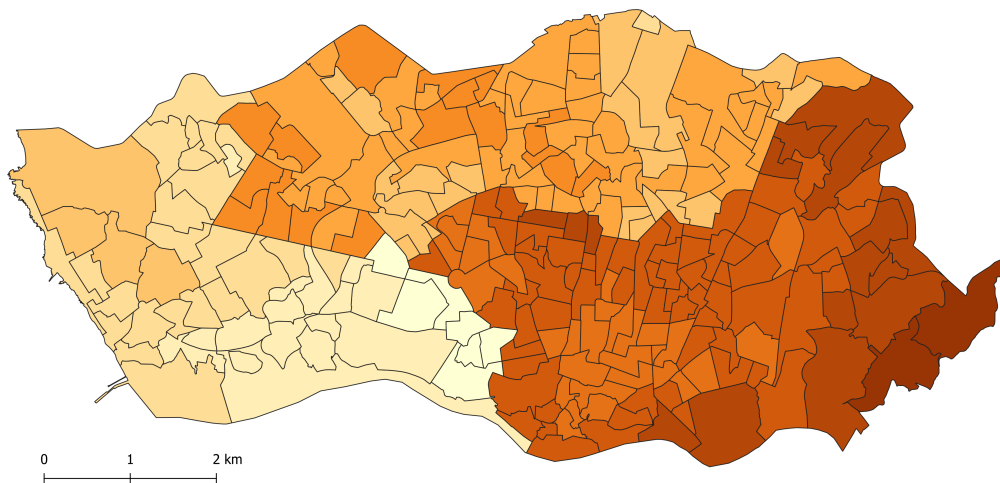


Figure A.2: Alternative 4: $\text{priority} = 0.3A + 0.1\text{PTF} + 0.1\text{IV} + 0.5\text{CAV}$

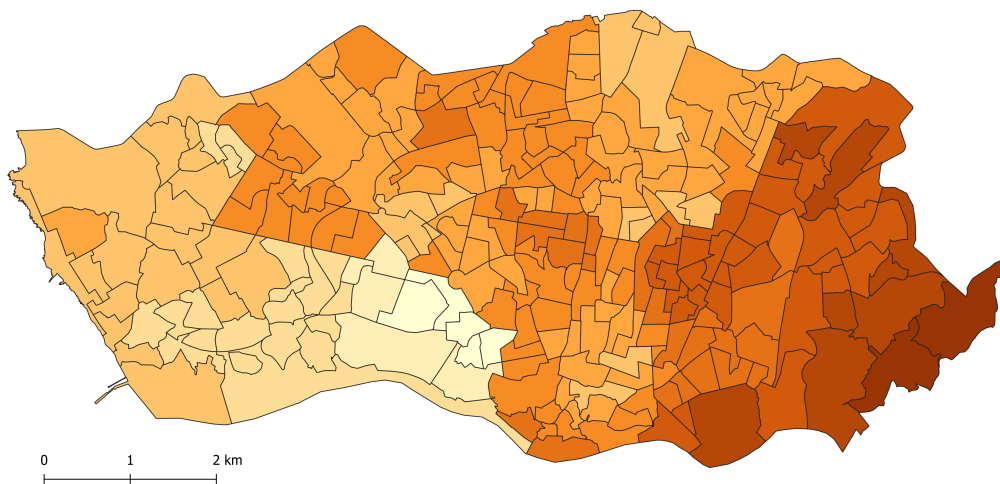


Figure A.3: Alternative 5: $\text{priority} = 0.3A + 0.2\text{PTF} + 0.4\text{IV} + 0.1\text{CAV}$

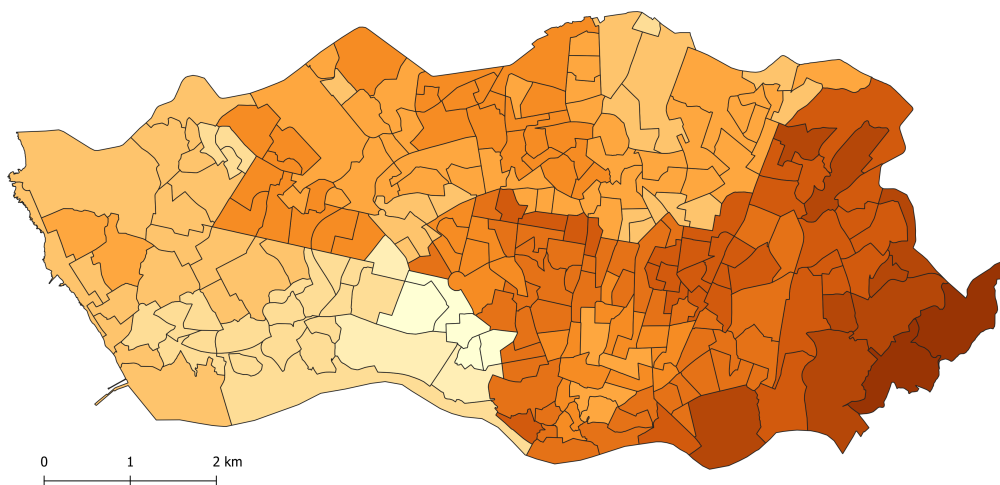


Figure A.4: Alternative 6: $\text{priority} = 0.3A + 0.2\text{PTF} + 0.1\text{IV} + 0.4\text{CAV}$

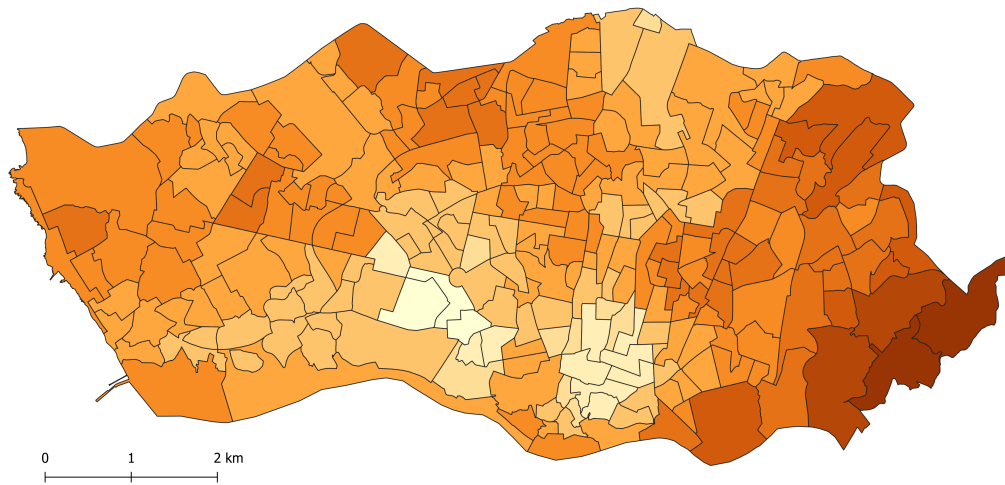


Figure A.5: Alternative 7: $\text{priority} = 0.3A + 0.4\text{PTF} + 0.15\text{IV} + 0.15\text{CAV}$

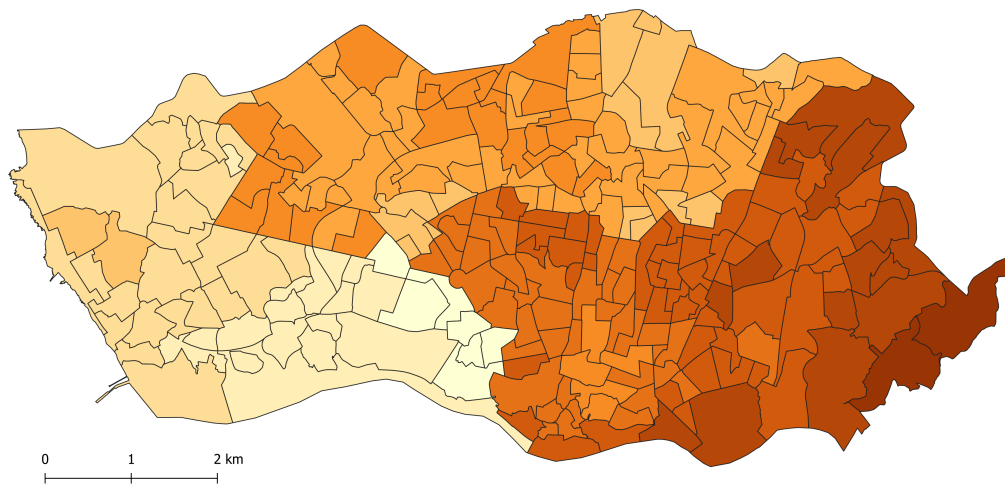


Figure A.6: Alternative 8: $\text{priority} = 0.3A + 0.1\text{PTF} + 0.3\text{IV} + 0.3\text{CAV}$

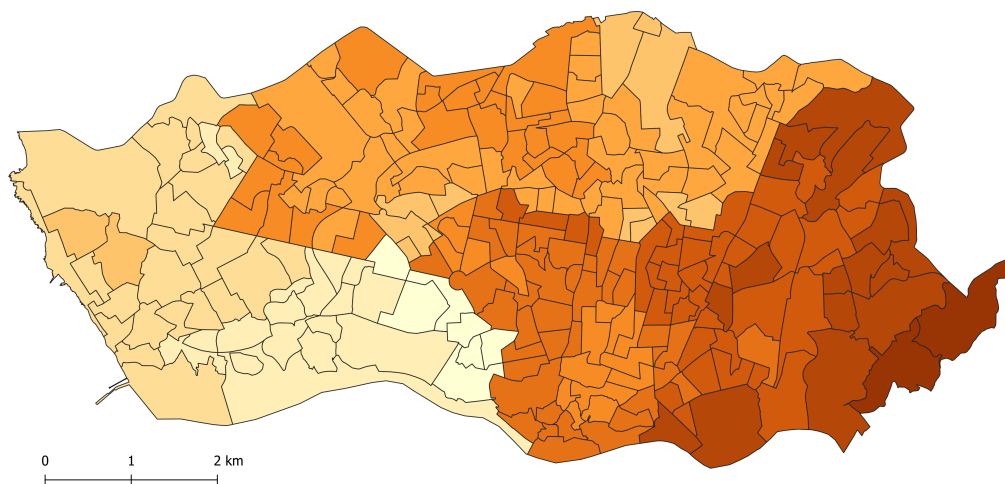


Figure A.7: Alternative 9: $\text{priority} = 0.3A + 0.1\text{PTF} + 0.4\text{IV} + 0.2\text{CAV}$

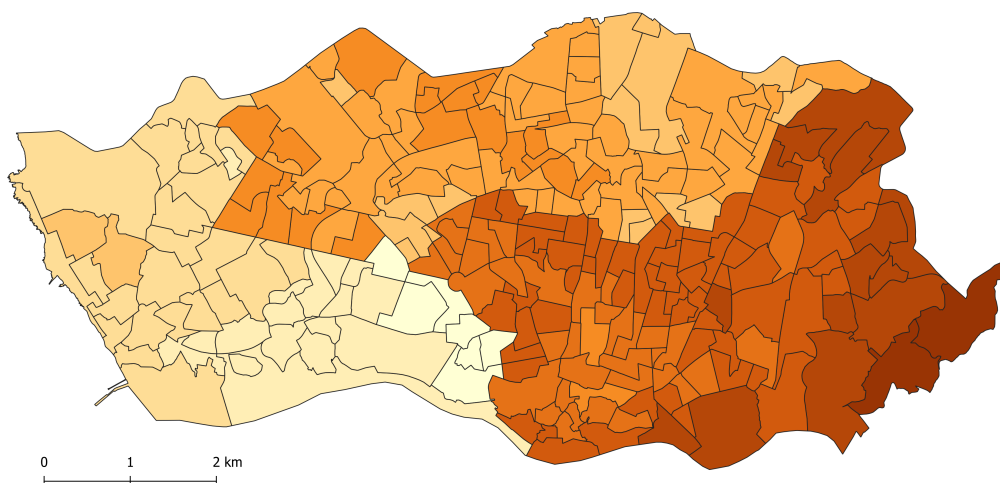


Figure A.8: Alternative 10: priority = $0.3A + 0.1PTF + 0.2IV + 0.4CAV$

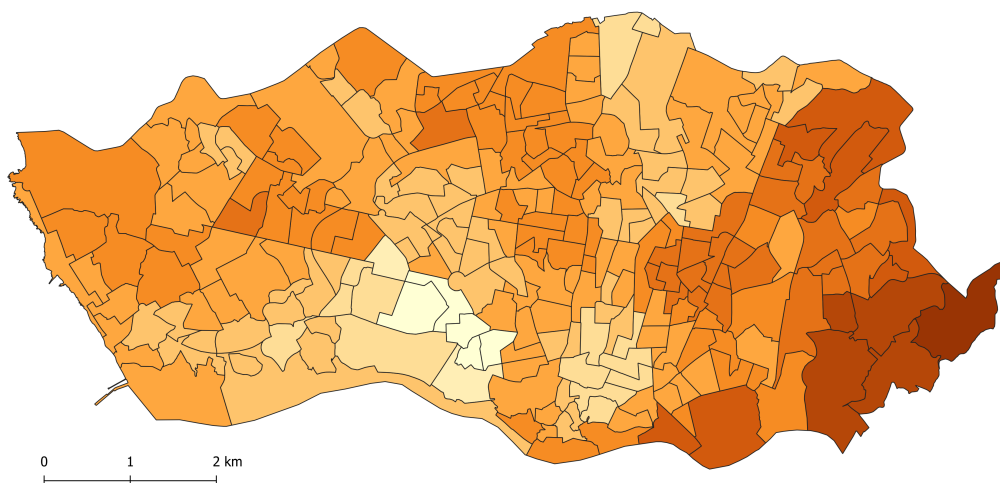


Figure A.9: Alternative 11: priority = $0.4A + 0.25PTF + 0.2IV + 0.15CAV$

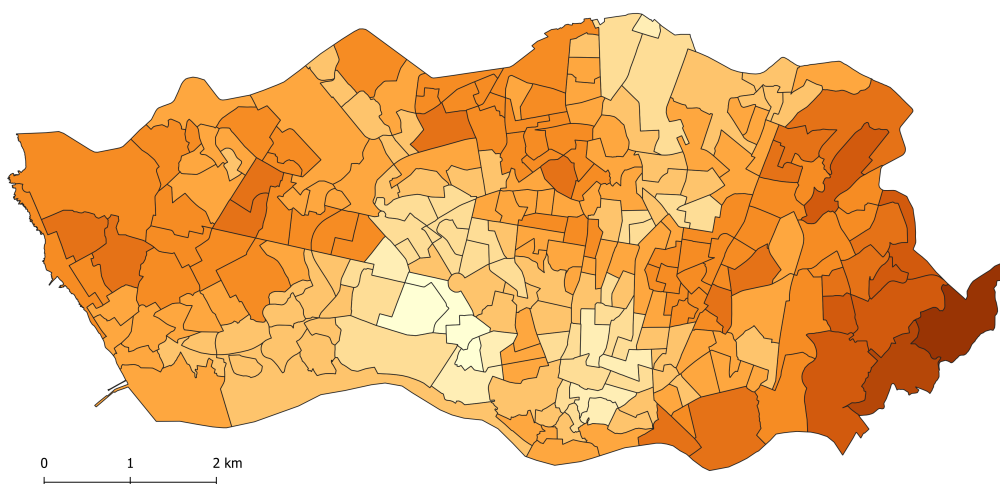


Figure A.10: Alternative 12: priority = $0.5A + 0.2PTF + 0.15IV + 0.15CAV$

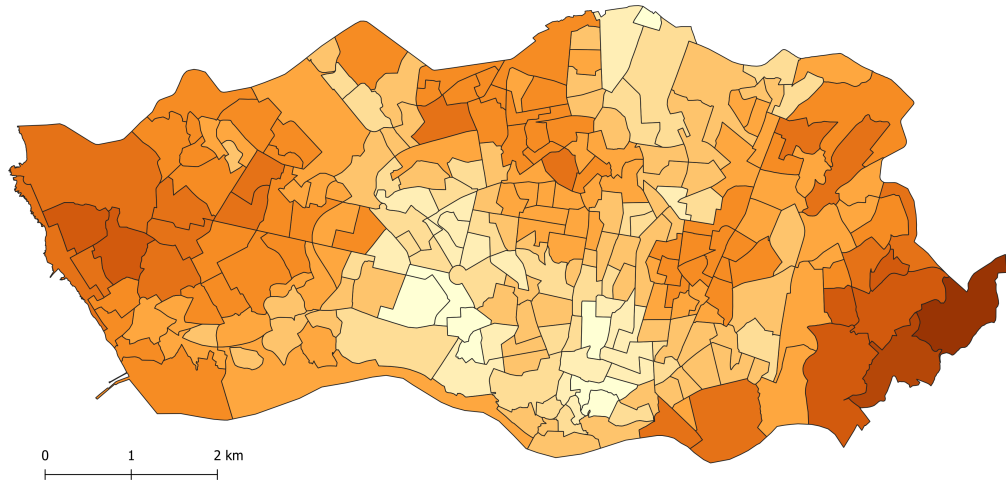


Figure A.11: Alternative 13: $\text{priority} = 0.6A + 0.15\text{PTF} + 0.15\text{IV} + 0.1\text{CAV}$

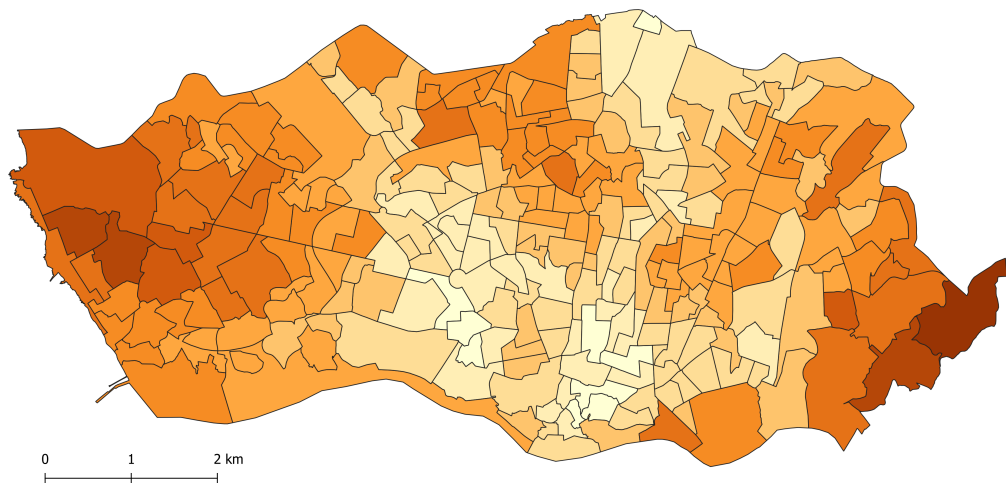


Figure A.12: Alternative 14: $\text{priority} = 0.7A + 0.1\text{PTF} + 0.1\text{IV} + 0.1\text{CAV}$

Appendix B

Sustainable Development Goals (SDG)

Table B.1: SDGs, goals, contributions and performance indicators

SDG	Goal	Contribution	Performance indicators and metrics
9	9.1 – Develop quality, reliable, sustainable and resilient infrastructure	This dissertation contributes to the development of more sustainable and integrated urban mobility systems by assessing how shared mobility services can complement conventional public transport. By comparing different policy scenarios, the work supports evidence-based planning of transport infrastructure and mobility services.	Changes in accessibility levels across policy scenarios; spatial coverage of mobility services; share of population or territory with improved access to public transport; comparison between baseline and integrated mobility scenarios.
10	10.2 – Promote the social, economic and political inclusion of all	The dissertation contributes to reducing inequalities by analysing how accessibility benefits are distributed across different territories. It helps determine whether integrating shared mobility services with public transport reduces or reinforces existing spatial disparities in access to opportunities.	Distribution of accessibility gains across municipalities, parishes, or statistical units; accessibility gaps between central and peripheral areas; identification of underserved areas; inequality measures based on accessibility percentiles, ratios, or distributional analysis.
11	11.2 – Provide access to safe, affordable, accessible and sustainable transport systems for all	This is the SDG most directly related to the dissertation. The work evaluates how shared mobility services can improve access to public transport and daily opportunities, particularly when used as first- and last-mile solutions. It therefore supports more inclusive and sustainable urban transport planning.	Accessibility to public transport stops and stations; accessibility to jobs, services or other opportunities within defined travel-time thresholds; population covered by improved accessibility; travel-time reductions between scenarios; comparison of accessibility under conventional public transport and integrated shared mobility scenarios.
	11.3 – Enhance inclusive and sustainable urbanization and integrated planning	The dissertation supports integrated urban and transport planning by assessing the spatial impacts of alternative mobility policy scenarios. The results can help identify priority areas for intervention and support more coordinated planning between shared mobility services and the existing public transport network.	Number of policy scenarios assessed; spatial distribution of accessibility impacts; identification of priority intervention areas; comparison of scenario performance according to accessibility and equity criteria; evidence of complementarity between shared mobility and public transport.