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LUCAS SOUSA FERREIRA

MEASURING ACCESSIBILITY AS A CAPABILITY: THEORETICAL AND PRACTICAL IMPLICATIONS FOR TRANSPORT JUSTICE

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Dissertação apresentada ao Programa de Pós-Graduação em Engenharia de Transportes da Universidade Federal do Ceará, como requisito parcial à obtenção do título de Mestre em Engenharia de Transportes. Área de concentração: Planejamento e Operação dos Sistemas de Transportes.

Orientador: Prof. Dr. Francisco Moraes de Oliveira Neto.

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Aos meus pais, Carlos e Francilene.
Aos meus avós, Carlos, Rita, Raimundo e Excelsa.

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Agora, no século XXI, a segregação dispensa chicote e polícia, basta a renda, ou melhor, a falta dela, a pobreza endêmica, a vida encerrada no círculo infernal da necessidade imediata – o pão, um chão onde deitar, a comida dos filhos, o confinamento imposto pela miséria, a liberdade supressa, a voz calada, a morte à espreita, quase bem-vinda.

(Frei Betto, 2006)

RESUMO

Embora a acessibilidade seja reconhecida como um fator determinante da equidade social, frequentemente sua avaliação é feita de forma simplificada, negligenciando heterogeneidades e condicionantes importantes que vão além do tempo de viagem. A literatura sobre justiça no campo dos transportes tem destacado o papel da abordagem das capacidades (AC) na consideração das restrições individuais na análise de acessibilidade, poucos estudos, porém, fizeram aplicações práticas neste campo. Como exemplo disso, nenhum estudo explorou a forma como a renda dos indivíduos, um determinante fundamental no acesso, impacta diretamente na acessibilidade, especialmente no contexto da abordagem das capacidades. Mesmo quando levada em consideração, a renda tende a ser analisada de forma agregada. Esse tipo de abordagem pode superestimar a acessibilidade dos indivíduos menos favorecidos e gerar vieses nas análises de equidade, e assim, subestimar as condições de pobreza e desigualdade na acessibilidade. Esta carência de aplicações empíricas resulta da ausência de propostas metodológicas, nos campos teóricos e práticos, para a medição da acessibilidade como capacidade. O presente trabalho tem por objetivo abordar estas questões.

Com base na abordagem das capacidades, foi proposto um framework para o desenvolvimento de medidas de acessibilidade que observem as heterogeneidades dos indivíduos no acesso às oportunidades. Como seria o padrão metodológico para o desenvolvimento de medidas de acessibilidade como capacidade? Para responder a esta pergunta, foi desenvolvido um framework com três vertentes. Em primeiro lugar, propõe-se uma definição formal para as medidas de acessibilidade como capacidade. Complementarmente, propõe-se então os critérios específicos para garantir a compatibilidade entre a abordagem das capacidades, as medidas de acessibilidade e os objetivos na avaliação da equidade. Por fim, sugere-se uma abordagem para operacionalizar o framework teórico, de modo a integrar a abordagem das capacidades no desenvolvimento de métricas de acessibilidade. Com isso, buscou-se contribuir para o avanço da discussão sobre a justiça nos transportes no âmbito teórico do desenvolvimento de indicadores de acessibilidade.

Partindo do framework proposto, avançou-se em uma proposta de método de operacionalização da abordagem das capacidades no âmbito da acessibilidade. A proposição metodológica consistiu no desenvolvimento de um indicador de acessibilidade como capacidade, bem como do seu método de aplicação. O indicador altera as medidas de oportunidades cumulativas de modo a considerar a gama de heterogeneidades dos indivíduos. O método proposto foi aplicado em um estudo de caso na cidade de Fortaleza (Brasil), analisando a acessibilidade ao emprego

dos chefes de família e explorando as possíveis implicações na análise de desigualdade e pobreza. Os resultados revelaram que, ao desconsiderar a renda e demais restrições individuais nas medidas de acessibilidade, a desigualdade na acessibilidade pode-se subestimar a desigualdade, medida pela razão de Palma, em mais de três vezes. Numa perspectiva de suficiência, a inclusão das restrições individuais também aumentou substancialmente a taxa de pobreza estimada.

Tais resultados tem duas implicações principais. Em primeiro lugar, ao não se considerar as restrições individuais, a condição real de privação no acesso às oportunidades enfrentadas pelos indivíduos é ignorada. Em segundo lugar, esses vieses nas análises de desigualdade e de pobreza na acessibilidade podem resultar em políticas que não abordam corretamente as injustiças urbanas. Assim, os resultados encontrados demonstram como a desconsideração do impacto das restrições individuais no acesso às oportunidades pode alterar substancialmente a avaliação de justiça, tanto do ponto de vista da análise de desigualdade quanto de pobreza. Isso evidencia a necessidade latente de avanços metodológicos na medição e avaliação da justiça no campo dos transportes.

Palavras-chave: acessibilidade; abordagem das capacidades; Rawls; equidade; justiça; medidas; políticas de transporte.

ABSTRACT

Although accessibility is recognised as a pivotal determinant of social equity, its evaluation is often oversimplified by neglecting heterogeneities and essential factors beyond travel time. Transport justice literature has emphasised the role of the capability approach (CA) in treating individual aspects in accessibility analysis, however, few studies have built practical applications in the field. For instance, no study has explored how individual income, a core determinant of access, directly impacts accessibility, especially in the CA context. Even when considering income, studies often focus on aggregate approaches that are based on averages. These approaches may overestimate the accessibility of the least advantaged and bias equity analyses by underestimating poverty and inequality. This lack of studies is a result of the dearth of both theoretical and operational methodological approaches on accessibility-as-capability measurement. This dissertation aims to address these issues.

We built on CA a comprehensive framework for accessibility measure development by observing individuals' heterogeneities in access. What should be the guiding design for shaping an accessibility-as-capability measure? To answer this question, we developed a three-fold framework. First, we propose a formal definition for accessibility-as-capability measures. Second, we propose specific criteria to ensure compatibility among CA, accessibility measures, and justice assessment purposes. Third, we propose an operational pathway to integrate CA into the development of accessibility metrics, thereby contributing to advancing the discourse on transport justice.

We advance CA operationalisation in the accessibility domain by building on the framework an accessibility-as-capability measure, in addition to a method of application. This measure adapts a cumulative opportunity measure (COM) to account for individual heterogeneity. We applied it in a case study regarding the job accessibility of the head of household in Fortaleza (Brazil) and analysed its implications on inequality and poverty analysis. The results revealed that, without accounting for individual constraints in accessibility measures, such as income and education, inequality in accessibility, as measured by the Palma ratio, might be underestimated by more than three times. From a sufficiency perspective, individuals' constraints inclusion also substantially raises the poverty rate in terms of accessibility, revealing up to 92.5% more people living in chronic poverty when compared to COM measure.

This finding reveals a two-fold implication. First, by not considering individual constraints, we do not know the real conditions of deprivation faced by the population regarding access to opportunities. Second, this bias in inequality and deprivation analyses could result in policies

that do not properly address injustices. These results demonstrate how not accounting for individuals' constraints on access could substantially change justice assessment from both equality and sufficiency perspectives and highlight the need for advancements in transport justice measurement and evaluation.

Keywords: accessibility; capability approach; Rawls; equity; justice; measures; transport policies.

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1 INTRODUCTION

1.1 Background

Justice theories have been applied to discuss about fairness on the public policies domain for a long time (Rawls, 2001, p. 02). As societies evolve, new areas have emerged in which justice concepts can be applied, providing more nuances to our understanding of freedom and equity.

In urban phenomena, accessibility has been linked to equity issues for at least five decades (Clark, 1976). Accessibility is a crucial metric of justice in the context of transport and urban policies to understand disparities between individuals (Martens, 2016, 2019; Pereira, Rafael *et al.*, 2019; Pereira; Karner, 2021). Fundamentally, accessibility measures individuals' potential to interact with or participate in opportunities and has four fundamental components: temporal, individual, transport, and land use (Geurs; Wee, van, 2004; Miller, 2018).

Despite this multidimensional aspect, accessibility studies often have focused primarily on travel time costs, overlooking important factors that impact access (Vecchio; Martens, 2021). Accessibility measures should capture not only the spatial and temporal dimensions but also the personal, economic, and social aspects that influence individuals' abilities to engage in activities (Dixit; Sivakumar, 2020; Luz; Portugal, 2022).

The literature underscores the substantial influence of some individual constraints on mobility potential, and a similar dynamic holds true in the realm of accessibility (Martens, 2016, p. 55). For instance, physical restrictions affect accessibility to people with disabilities and older people (Ma, Kent; Mulley, 2018). Monetary constraints affect individuals' access to mode options, thus reducing their accessibility (Bocarejo *et al.*, 2014; Bocarejo; Oviedo, 2012; Herszenhut *et al.*, 2022; Luz; Portugal, 2022). Social roles related to gender affect women's disposable time to engage in job activities due to childcare responsibilities (Robeyns, 2008a). By overlooking these access determinants, accessibility studies introduce biases on justice assessment, often resulting in an underestimation of inequality and poverty.

The prevailing discourse on accessibility reveals a significant gap, characterised by an incomplete consideration of various limiting factors and constraints that substantially hinder individuals' access to opportunities. Notably, this gap is evident in the neglect of essential components, including affordability, as well as critical group inequality factors, such as physical conditions and social norms, that effectively shape accessibility in practice.

In the justice context, the Capability Approach (CA) has emerged as a promising framework for addressing these issues by focusing on the real opportunities and capabilities of individuals (Robeyns, 2013). A growing body of transport literature has endorsed the moral connection between CA and accessibility (Beyazit, 2011; Cooke *et al.*, 2022; Luz; Portugal, 2022; Pereira, Schwanen; Banister, 2017; Vecchio; Martens, 2021), offering a moral rationale for connecting them.

The literature has underscored the need for advancements in accessibility measurements for justice assessment (Martens; Golub, 2012; Neutens *et al.*, 2010; Pereira, Schwanen; Banister, 2017). In this sense, it is important to note that, despite many works advance in build a theoretical dialogue between CA and accessibility literature, none of them delved into specific theoretical issues regarding accessibility measure development to account for CA and access constraints. They did not provide practical guidelines or criteria for measures development. The formal foundation for the development of accessibility-as-capability measures remains elusive.

Furthermore, the practical implementation of CA in the field of transportation remains restricted, primarily because of the complexities involved in developing measures that effectively incorporate individual characteristics (Deka, 2022; Dixit; Sivakumar, 2020). This is also a result of the lack of theoretical guidelines. These gaps underscore the need to bridge the theoretical and practical realms and clarify the criteria and considerations essential for advances in CA applications on accessibility.

How should accessibility measures appear to encompass the capability approach in relation to heterogeneities and real opportunities of individuals? This work embarks on a journey through the intricate interplay between justice theories and accessibility measurement. It seeks to shed light on some of the complex dimensions of justice in transportation, emphasising the importance of comprehensive accessibility measures that consider individual constraints. In doing so, it aspires to contribute to the broader discourse on justice within transportation policies, inspiring further research and development in the pursuit of equitable and inclusive transport systems.

1.2 Aims and scope

The overarching aim of this dissertation is to provide a theoretical and practical pathway to account for CA on accessibility measurement domain accounting for individuals heterogeneities. This primary objective translates into three specific aims. The first is to propose a capability approach framework for the development of accessibility measures. This

framework aims not only to offer theoretical specifications, but also to describe criteria and give practical directions to accessibility-as-capability measures development. The second is to advance methodological issues by proposing an accessibility-as-capability measure based on the proposed theoretical framework. The third is to investigate the impact of the proposed measure on justice assessment of inequality and poverty in a case study on job accessibility in Fortaleza (Brazil).

1.3 Chapters overview

This dissertation is organized into four chapters. The first is this introduction. Chapter 2 presents the theoretical foundation and addresses the first aim. It reviews previous studies on CA and justice applied to accessibility, supporting the discussion. Based on capability approach theory and political philosophy literature, as well as in previous theoretical works on accessibility, we provide a formal specification and measurement criteria to accessibility-as-capability measures. It also highlights some operational directions for practical advancement using this framework. Chapter 3 builds upon the theoretical framework to propose an accessibility-as-capability measure to account for different individual constraints, referring to the second aim. The chapter also provides methodological advancements related to data scarcity in CA operationalisation. An empirical application through a case study on Fortaleza (Brazil) was realised to exemplify the operationalisation of both accessibility measure and theoretical framework. In this case study, we investigated how accounting for different individual constraints impacts justice assessments. This case study focuses on the impact of factors such as individuals' monetary and educational constraints on job accessibility. We then compare the results of inequality and poverty measures when employing the proposed and alternative measures.

2 MEASURING JUSTICE THROUGH ACCESSIBILITY: A CAPABILITY APPROACH THEORETICAL FRAMEWORK

2.1 Introduction

Accessibility is constrained by several factors that lead to inequality and poverty. Luz and Portugal (2022) listed a range of elements that can generate accessibility deprivation, such as economic, geographical, physical, and temporal constraints. Despite this, accessibility studies often disregard many of these elements by focusing primarily on travel time costs and overlooking other factors that limit access (Vecchio; Martens, 2021).

Economic resources are one of the main sources of transport-related social exclusion, restricting accessibility, especially for low-income people due to affordability issues (Bocarejo *et al.*, 2014; Bocarejo; Oviedo, 2012; Falavigna; Hernandez, 2016; Guzman; Oviedo, 2018; Luz; Portugal, 2022). In this sense, do we consider access when calculating accessibility measures without considering people's monetary constraints? Prevailing accessibility measures often states that these people have opportunities when some of them do not even have the financial conditions to pay for the fare. These considerations directly impact justice assessments and what we consider fair systems.

The discussion of how resource availability impacts justice is a theme that is easily associated with John Rawls' theory of justice. Rawls' theory focuses on the distribution of primary resources, such as income, wealth, and opportunities, and argues in favour of the priority of the least advantaged (Rawls, 1999). Previous studies have discussed Rawl's theory and its implications for transport justice assessment (Martens, 2016; Martens; Golub, 2012; Pereira; Schwanen; Banister, 2017; Wee, Van, 2022). These studies highlight the importance of promoting equity by improving access to opportunities for low-income people.

Meanwhile, a growing number of studies on transport justice advocate for the capability approach (CA) (Azmoodeh; Haghighi; Motieyan, 2023; Cao; Hickman, 2019; Cooke Et Al., 2022; Deka, 2022; Hananel; Berechman, 2016). CA is a multipurpose normative framework that focuses on the real opportunities of individuals and is not precisely a theory of justice or well-being (Robeyns, 2013, p. 456). CA theorists advocate that CA can account for the range of individuals' needs to evaluate their opportunities, providing a more complete view of individuals' constraints on justice assessments in relation to approaches focused on resources, such as Rawl's theory (Anderson, 2010).

Literature underscores the significance of the relationship between accessibility and CA in the realm of transport justice (Luz; Portugal, 2022; Pereira, Schwanen; Banister, 2017; Vecchio; Martens, 2021). These studies provide a moral rationale for the connection between CA and accessibility, explaining its effects on transport analysis, and building a parallel between the original political philosophy concepts. However, none of these studies has offered a formal foundation for the construction of accessibility-as-capability measures or for enhancing existing accessibility metrics to better incorporate considerations of individuals' constraints and related factors.

CA and political philosophy literature shows a range of factors (or principles) to be accounted for in measures to justice evaluation, such as objectivity and individual level of aggregation (Anderson, 2010; Robeyns, 2006). In addition to these criteria, important issues related to access considerations must be addressed to ensure compatibility with CA in the development of accessibility measures.

Beyond disparities between CA and Rawls' theory, Pereira et al. (2017) argue that a convergence between the theories could address concerns related to social exclusion and distributive justice in the transport domain by focusing primarily on "accessibility as a human capability". In this convergence, the authors highlighted the implications of both theories on transport and argued that accessibility as a capability is a central metric of transport justice, though not the only one. However, their work did not delve into theoretical specifications for accessibility metrics, highlighting the need for further exploration of this issue (Martens; Golub, 2012; Pereira, Schwanen; Banister, 2017).

Robeyns (2008, p. 398-412) argues that a capability approach view can build this convergence by incorporating the primary resources of Rawls' theory. According to the author, in this convergence, income and wealth will not be important by themselves but rather because of their crucial instrumental role in capabilities.

Given this context, the present study aims to contribute to previous theoretical efforts in the transport literature by proposing a capability approach framework for the development of accessibility measures. This framework advances the theoretical convergence between CA and Rawl's theory on the domain of accessibility by acknowledging the instrumental role of income on accessibility-as-capability measures. It also provides a formal specification of accessibility-as-capability measures and attempts to consolidate the theoretical relationship between the CA and accessibility measures. In addition, we suggest directions for operationalising this framework.

The remainder of this chapter is organised as follows. Section 2.2 builds a theoretical background on distributive justice and reviews key theoretical applications of the capability approach in the transport context, along with other relevant works. In Section 2.3, we briefly discuss the monetary role of accessibility from the CA perspective. Section 2.4 introduces the framework outlined in this study. Finally, Section 2.5 presents conclusions and identifies directions for further research.

2.2 Distributive justice on transportation

A theory of distributive justice must specify at least two parameters: a metric and a rule (Anderson, 2010, p. 81). The metric of justice refers to the goods being compared between individuals, such as income and wealth, whereas the distributive rule specifies criteria for the fair allocation of these goods among individuals (Anderson, 2010, p. 81). Equality, sufficiency, and priority for worst-off are examples of distributive rules (Robeyns, 2013, p. 457).

These concepts are important when discussing political philosophy theories. In the present work, they were applied to discuss two of the most relevant theories of Transport Justice: the capability approach and Rawls' Theory (Nahmias-Biran; Martens; Shiftan, 2017; Pereira; Schwanen; Banister, 2017; Terzi, 2010, p. 150).

2.2.1 Rawls and the principles of justice

Rawls' "A Theory of Justice" has been a central topic in political philosophy for the last fifty years, and subsequent theories use it as a basis for discussion (Kymlicka, 2002, p. 10; Martin, 2013, p. 401). Many authors have discussed the implications of Rawl’s theory in transport planning (Martens, 2016; Nahmias-Biran, Martens, And Shiftan, 2017; Pereira, Schwanen, And Banister, 2017). Therefore, we focus on the essential theoretical components necessary for subsequent discussions and the proposed framework.

According to Rawls, justice precepts that all social values, including freedom, opportunity, income, and wealth – the primary goods – should have an equal distribution unless an unequal distribution is advantageous to all (Rawls, 1999, p. 54). His theory is based on two principles of justice that can be understood as a special case of Rawls’ general concept of justice (Rawls, 1999, p. 54).

The first refers to the principle of equal basic rights and liberties, a condition for achieving a just and fair democratic society. The second principle states that economic and social inequalities must satisfy two conditions:2a) they must be linked to conditions of equal opportunity and 2b) they must lead to the greatest benefit for the least advantaged – the so-

called difference principle (Rawls, 2001, p. 42-43). In simple terms, least advantaged individuals have the lowest income and wealth (Rawls, 2001, p. 59).

An important point regarding these principles is the priority (known in the literature as lexical priority) assigned by Rawls. The first principle has priority over the second one. Principle 2a, of opportunities, has priority over 2b, the principle of differences. To apply some of these principles, it is assumed that the previous one is fully satisfied (Rawls, 2001, p. 43).

Thus, the metric of justice in Rawls' theory are the primary goods, a combination of disposable income and opportunities, with a diversity of human rights and the social basis of self-respect (Anderson, 2010; Robeyns, 2017a). Rawls' theory focuses on the distribution of these goods, and argues in favour of the priority of the least advantaged (Rawls, 1999).

Previous studies have discussed Rawl's theory and its implications for transport justice assessments (Martens, 2016; Martens; Golub, 2012; Pereira, Schwanen; Banister, 2017; Wee, van, 2022). These studies highlight the importance of promoting equity by improving access to opportunities for low-income people.

2.2.2 The capability approach

According to Robeyns (2013, p. 456), the capability approach can be understood as a "flexible and multipurpose normative framework, rather than a precise theory of well-being, freedom, or justice". At its core, this approach outlines five fundamental concepts: resources, conversion factors, capabilities, choices, and functionings (Robeyns, 2005; Vecchio; Martens, 2021). Resources, are the "means to achieve", or the "capability inputs", such as income, goods, and services (Robeyns, 2005; Vecchio; Martens, 2021). These are attributes of capabilities that are often more easily commensurable (e.g., income, goods).

According to Sen, Rawls' theory fails to account for individuals' diversity in the conversion of resources to real opportunities (Robeyns, 2008b, p. 403-404). In CA, conversion factors related to personal, social, and environmental aspects dictate people's potential to convert resources into capabilities (Robeyns, 2008b, p. 404; Vecchio; Martens, 2021).

This multidimensionality makes it more difficult to account for conversion factors (Dang, 2014). Their application in measurements occurs by estimating the conversion rates between resources and capabilities. These conversion rates can work as control variables (or parametric variables) or even as quantitative and binary variables (Comim, 2008; Dang, 2014).

Capability is the core idea and refers to "what people are effectively able to do and be", the real freedom available to individuals, or their real set of choices (Robeyns, 2003). Functionings, on the other hand, are the actions performed by individuals among their

capabilities that result from their choices (Robeyns, 2003, 2006, 2008b). Functionings, unlike capabilities, are observable; therefore, they are more easily measured than capabilities are (Robeyns, 2003). Choices are attributes of individuals that enable them to select within their set of capabilities.

While other theories focus on subjective issues, such as utility, in utilitarianism, or on the means to achieve well-being, such as resources in Rawls' theory, the capabilities approach focuses on the freedom of individuals and on their genuine opportunities to perform activities (Deka, 2022; Robeyns, 2005; Sen, 1995, p.81).

According to Robeyns (2013, p. 464), unlike Rawls' theory, CA focuses only on the metric of justice (capabilities) and does not specify a rule of distribution, although some authors suggest that the theory implies a sufficientarian rule. This imprecision also occurs in the transport field (Hananel; Berechman, 2016; Nahmias-Biran, Martens; Shiftan, 2017; Vecchio; Martens, 2021).

Anderson (2010, p. 87-88;97) argues that capabilities are superior to resources as a metric of justice. The author argues that capabilities capture social injustices, such as exclusion and social norms, better than resources. She also argues that people often demand capabilities rather than just resources when they make claims of justice.

In the transportation literature, some authors have contrasted the implications of CA and Rawls' theories in the field (Basta, 2016; Beyazit, 2011; Pereira, Schwanen; Banister, 2017). Therefore, our goal is not to contrast these theories but to comprehend their features in order to contextualise our framework. For this purpose, we employ the general concept of the capability approach as a "general, open, underspecified approach" that can facilitate the creation of a specific "capability application" (Robeyns, 2017, p. 29) and use the concepts of Rawls' theory to discuss the existing frameworks.

2.2.3 The metric and the rule in transportation justice

Capability theorists and practitioners need to choose the metric between functionings or capabilities or use a combination of both (Robeyns, 2013, p. 464). Although both functionings and capabilities have compelling arguments (Robeyns, 2006), for justice issues, capabilities should be prioritised over functionings (Robeyns, 2008, p. 404).

In recent years, more studies have analysed and applied CA to transportation field, many of which outline empirical and theoretical relationships with accessibility concepts (Cao; Hickman, 2019; Chen; Akar, 2017; Deka, 2022; Nahmias-Biran, Martens; Shiftan, 2017;

Pereira, Schwanen; Banister, 2017; Randal *et al.*, 2020; Vecchio, 2020; Vecchio; Martens, 2021).

Accessibility is a key measure of justice for transportation, according to many authors who prefer it over other metrics, such as mobility, activity space, and transportation resources (Chen; Akar, 2017; Martens, 2016, 2019; Pereira; Karner, 2021; Pereira, Schwanen; Banister, 2017; Vecchio; Martens, 2021). Accessibility reflects individual capabilities and freedom better than functionings (such as mobility) and resources (such as car ownership or activity space) because it captures the opportunities that individuals have.

Although the distribution rules are not the primary focus of this work, we need to understand the main approaches and their implications to examine justice frameworks in the transportation literature. Sufficientarianism, in its "pure" form, holds that there is a minimum amount of benefits that everyone should have and that any distribution with less or equal insufficiency is equally just (Vallentyne, 2009, p. 143). Therefore, a fair system must ensure a basic level of accessibility (Nahmias-Biran, Martens; Shiftan, 2017; Pereira, Schwanen; Banister, 2017).

Some authors in the transportation justice literature have argued that a democratic approach is crucial in establishing an accessibility threshold and noted that many works on this topic assume a “technocratic” and paternalistic approach, which is a common limitation (Martens, 2016; Pereira; Karner, 2021). Therefore, the accessibility threshold definition remains a question in transportation literature (Hananel; Berechman, 2016; Miller, 2018; Pereira, Schwanen; Banister, 2017), although some empirical efforts have claimed to be based on a sufficientarian process of evaluation (Lucas, Wee, van; Maat, 2016; Singer, Cohen-Zada; Martens, 2022; Veen, van der *et al.*, 2020).

On the other hand, egalitarianism proposes that justice is concerned with the relative distribution of benefits among individuals (Pereira; Karner, 2021). The current debate over equality assumes that some level of equal distribution is necessary (Anderson, 2012, p. 40), and has been focused on moving from equality of outcomes to equality of opportunities – the famous “equality of what?” question (Roemer; Trannoy, 2015, p. 218). Transportation applications that claim to be based on egalitarian assumptions are generally not properly grounded in political philosophy. These studies have frequently failed to define what constitutes an unfair condition in a transportation system (Pereira; Karner, 2021).

2.2.4 Frameworks review

Pereira et al. (2017) propose a framework that combines Rawls' theory of justice and the capability approach to create an ethical perspective in transportation justice. They argue that accessibility can be viewed as a primary good from a Rawlsian perspective, and that transportation justice concerns how transport policies address inequalities in access to opportunities. According to the authors, fair transportation interventions and policies improve accessibility for the least advantaged. They also advocated the need for a minimum level of accessibility as a way to guarantee access to basic destinations.

From a CA perspective, Pereira et al. (2017) argue that accessibility can be understood as a combined capability that considers individual characteristics, social factors, and other constraints. They advocate a sufficientarian and prioritarian approach, understanding the least advantaged as low-income. The framework presented by the authors makes a structural contribution to linking Rawls' theory and CA in the transportation field, allowing discussions about the implications for accessibility assessments. Their emphasis, however, was not on diving into the specification of accessibility as a capability metric of justice but on giving a moral rationale for its importance as a transportation justice concern. Therefore, further studies are required (Pereira, Schwanen; Banister, 2017).

Randal et al. (2020) presented a justice theoretical framework for transportation policies which according to the authors was based on the work of Pereira et al. (2017). Their core idea is that public policy should enhance capabilities and not just focus on accessibility. They argue that viewing transport policies as conversion factors, rather than solely focusing on accessibility, provides a wider perspective on their effects and externalities, while also considering a more comprehensive set of capabilities (Randal *et al.*, 2020).

According to Vecchio and Martens (2021) the accessibility-focused approach is preferable to the one presented by Randal et al. (2020), because the latter does not provide guidance on how to prioritise the various impacts on the set of capabilities and related factors. This lack of definition of the set of capabilities to be considered, such as accessibility, mobility, and health listed by the authors, leaves those who intend to apply the framework to solve a question presented by Sen (2004, p. 78) and Robeyns (2006, p. 357) – the weighting or indexing issues among capabilities.

For instance, if a policy enhances accessibility, but has health implications, how can we determine its fairness? Similarly, if there is insufficient accessibility to jobs and healthcare, which should be prioritised? Therefore, valuing capabilities cannot be avoided, which makes

the weighting of capabilities an issue in transport justice (Nahmias-Biran, Martens; Shiftan, 2017).

Vecchio and Martens (2021) proposed an application of capability theory in the field of transportation focused on accessibility as a capability. They proposed an evaluative process that combines two analytical views of accessibility as a capability: a top-down approach that evaluates accessibility at the aggregated level of the transport and land-use system and a bottom-up approach that examines individuals' perceived accessibility.

Although the top-down approach does not address the individual claim intrinsic to the capability approach (see section 2.4.2.3), the authors justify the application of this approach as a way to detect inequalities in relation to specific groups. This strategy is used in empirical CA applications (Comim, 2008, p. 178) and can be useful in transport policies in specific cases, especially if used in combination with individual analysis. However, this method cannot assess individuals' capabilities but only group differences in capability levels (Robeyns, 2008b, p. 409).

Vecchio and Martens (2021) view income, a primary good presented by Rawls, as a conversion factor. This differs from the general capability literature, which considers income as a resource (Robeyns, 2005, 2008, p. 409; Sen, 2011). According to Robeyns (2005), resources such as goods and services are understood as "capability inputs ".

The bottom-up approach specifies the metric of justice as a subjective accessibility measure, presenting it as a capability (Vecchio; Martens, 2021). This subjectivity leads to problems such as adaptive preferences (Comim, 2008, p. 173), a well-known bias in transportation literature (Ryan; Pereira, 2021). This bias tends to perpetuate inequalities, offering little support to those who have less because deprivation makes them less rigorous with living standards (Robeyns, 2018).

van Wee (2022), otherwise, proposes a flexible framework of accessibility that is not tied to a specific theory of justice in order to define the important factors in equity studies. Within this framework, the author added the concept of digital access, which has the potential to increase individuals' opportunities without physical contact. The author, like Vecchio and Martens (2021), focused on perceived accessibility to address transportation equity concerns.

Luz and Portugal (2022) proposed a framework that establishes a theoretical foundation for examining transport-related social exclusion (TRSE) from a CA perspective. They identify ten different dimensions of the TRSE that allow us to understand how individuals could be prevented from travelling and accessing opportunities. The list of dimensions included

geographical, physical, and economic factors. These factors are important for understanding accessibility in the context of capabilities.

However, none of these studies provide formal methodologies to directly integrate capability considerations into accessibility measures. Given the various criteria required for justice assessments, such as objectivity and publicity (Anderson, 2010; Comim, 2008), the absence of specific guidelines regarding the precise impact of incorporating capability approach criteria into accessibility metrics poses a theoretical challenge.

2.3 The monetary aspect

Considering the significance of income as a primary good in Rawls' theory of justice, it is essential to contextualise the monetary dimension from a capabilitarian perspective of accessibility. It is also important to specify its role in the development of accessibility-as-capability measures.

Unlike the standard concept of poverty in economics, which focuses on goods such as income and wealth, the capabilitarian view conceptualises poverty as the deprivation of basic capabilities (Sen, 1995, p. 9). This concept shifts from an instrumental view of poverty, based on disposable income, to an intrinsic view, focusing on the lack of capabilities, rather than resources.

Despite disagreement regarding the use of resources as a metric of justice, as argued by Rawls, CA literature assumes that income is “one of the major causes of poverty” and plays an important role in capability deprivation (Sen, 1999, p. 87). As a result, Robeyns (2008, p. 412) argues that it is possible to build a framework that converges CA and Rawls’ theory by treating income and other primary goods as inputs for capabilities and functionings. This could be done by analysing the inputs and determinants of capabilities (Robeyns, 2008b, p. 409).

We can understand individuals’ monetary budgets as one of the main inputs to capability (Kuklys; Robeyns, 2005, p. 10-18). In general accessibility literature, monetary issues are considered through the concept of affordability. Transport affordability represents the mediation between individuals' financial resources and transportation costs, which dictates access to mode options (Falavigna; Hernandez, 2016).

Affordability have a significant impact on accessibility, especially for low-income people, depriving them of access to transport and opportunities (Bocarejo; Oviedo, 2012; Falavigna; Hernandez, 2016; Guzman; Oviedo, 2018; Luz; Portugal, 2022). Its impact is often disregarded, which generates biases in accessibility assessments (Herszenhut *et al.*, 2022).

However, it is important to note that transport affordability does not fully account for the set of goods and needs of individuals, such as housing and food, which must be considered to understand if transport is affordable. In this sense, some authors have claimed that transportation and housing affordability should be treated as a combined urban problem confronting individuals to comprehend the true conditions available to them as a result of their income (Coulombel, 2018; Mattingly; Morrissey, 2014).

Previous studies on capability have already incorporated monetary issues as inputs to capabilities metrics by considering the monetary budget constraints of individuals (Kuklys; Robeyns, 2005; Sen, 1985). However, this has not yet been observed in CA applications to accessibility.

2.4 Framework proposal

The difference principle of Rawl's theory defines which inequalities should receive attention and which can be justified, based on the argument that inequalities are only acceptable when they benefit the less advantaged. The capability approach offers a more comprehensive perspective for assessing people's opportunities. It emphasises capabilities, which, in the context of transportation, closely align with accessibility. This approach provides a clearer understanding of individuals' real opportunities and ability to access transportation options, making it particularly relevant for transportation planning and policy.

In contrast to earlier frameworks, our approach focuses on providing a structured framework for developing accessibility-as-capability measures. We do not focus on distributional considerations, as in previous frameworks. Thus, distributional concerns are discussed based on prior literature, particularly the framework introduced by Pereira et al. (2017), due to the established connection between Rawls' theory and CA in the context of transportation.

2.4.1 Accessibility-as-capability formalization

Based on the works of Sen (1985, p. 9) and Kuklys and Robeyns (2005, p. 10-12), and given the earlier discussions, we propose a formal definition for accessibility-as-capability measures in Equation 1.

$$\boldsymbol{A}_{ip} = f_{ip}\,(\boldsymbol{x_i}, \boldsymbol{z_i}), \qquad \forall\, x_i \in \boldsymbol{X}_i \,\forall\, z_i \in \boldsymbol{Z}_i \tag{1}$$

$$\boldsymbol{A}_i = \left\{ f_{ip}\left(\boldsymbol{x_i}, \boldsymbol{z_i}\right); p \in \mathbf{P} \right\} \quad (2)$$

Where:

$A_{ip,}$ is the measure of accessibility-as-capability of individual *i* to activity *p;*

A_i, is the set of accessibility-as-capability measures of individual *i* to all activities *p*;

X_i, is the set of accessibility resources (and their characteristics) of individual *i*, i.e., monetary budget (br_i), transport (tr_i), land-use (lr_i), and time budget (tbr_i);

Z_i, is the set of conversion factors related to individual i, i.e., personal (pf_i), social (sf_i), and environmental factors (ef_i);

f_{ip}, is the accessibility-as-capability function.

Equation 1 defines accessibility-as-capability value (A_{ip}) for individual i and activity p. This indicates that accessibility-as-capability functions, f_i, must have two inputs: the individual's resource set, x_i , and conversion factors, z_i. By applying these factors to an individual's resource set using the function f_i, the proposed fundamental concept of accessibility-as-capability measurement is stablished.

These measures can be grounded in different accessibility methods found in the literature, such as cumulative opportunity measures and gravity-based measures. However, it is crucial to consider the distinct criteria, limitations, and adaptation requirements, which are discussed in Section 2.4.2 and Section 2.4.3.

An individual capability set should be restricted by its resource set, x_i (Sen, 1985, p. 9). In terms of accessibility, this set comprises the monetary budget (br_i), transport resources (tr_i), land-use resources (lr_i), and time budget (tbr_i). Since transport, land use, and time represent three of the four components of accessibility measures, with the monetary budget being part of the fourth component (Geurs; Wee, van, 2004), it becomes evident that accessibility applications are predominantly concerned with resource-related evaluations (Martens; Golub, 2012).

The monetary budget (br_i) refers to the disposable income of individuals to transport and activities, and depends on different factors, not properly related to transportation (e.g., food, clothing, and health care), and accounts for affordability issues discussed in Section

2.3. This component directly or indirectly affects access to other resources such as mode options and housing.

Transport resources (tr_i) include both the public and private mobility options available to individual i. Broadly, public transport resources include services such as bus systems, taxis, and shared mobility options (Cooke *et al.*, 2022; Vecchio; Martens, 2021). Private transport resources range from bicycles and wheelchairs to motor vehicles and other modes of transportation.

Land-use resources (lr_i) represent the spatial distribution of activities and their characteristics (e.g. opening hours, educational requirements, location) related to the land-use component of accessibility (Geurs; Wee, van, 2004). In addition, land-use resources should encompass housing options, an important resource in capabilities, specially to accessibility (Kimhur, 2020; Coulombel, 2018; Mattingly; Morrissey, 2014).

Time budget resource (tbr_i) refers to the disposable time that people have to travel and engage in activities, and is part of the temporal dimension of accessibility (Geurs; Wee, van, 2004). They depend on diverse conversion factors, such as work and family obligations, daylight saving time policies, and the relationship with individuals' travel time, as well as on other resource characteristics, such as the schedules of activities and opening hours.

Conversion factors (z_i) mediate between resources and capabilities, and are key features of CA that highlight human diversity, also understood here as a range of non-monetary constraints (Kuklys; Robeyns, 2005, p. 11). In this sense, accessibility-as-capability should encompass the 'sources of diversity between human beings' presented by Comim (2008), related to personal, social, and environmental conversion factors, which range from the level of education to social norms.

According to Robeyns (2017, p. 46), personal conversion factors (pf_i) are related to the characteristics of a person, such as physical condition, gender, and intelligence. Sen called 'conversion handicap' the impedance that some of these factors can impose to converting incomes and resources into capabilities (Sen, 2011, p. 258).

For instance, individuals with physical disabilities might require a higher transportation budget for more suitable options such as taxis or adapted vehicles, rather than using public transit, to achieve the same level of accessibility as those without disabilities. Consequently, the conversion rate of monetary resources into accessibility for these individuals is lower than that for those without disabilities.

Environmental conversion factors (ef_i) encompass elements of the physical and built environment, such as infrastructure, weather, climate, and rivers (Robeyns, 2017, p.46).

Some of these factors directly affect accessibility and can include elements such as bus stops, bike racks, roads, bus lanes, cycle lanes, sidewalk slopes, terrain relief, and the presence of waterways.

Social conversion factors (sf_i) are external to the individual and are related to societal conditions to which individuals are subject, such as public policies, social norms, power relations, and discriminatory practices based on gender, race, and class (Robeyns, 2017, p. 46). Elements such as fare policies, gender roles, and public safety can influence accessibility by affecting monetary and time budgets as well as personal freedom.

Finally, Equation 2 defines the accessibility-as-capability set A_i, recognising the multifaceted nature of capabilities, encompassing all potential purposes and activities that individuals require, such as jobs and education. This multipurpose aspect of the capability set is also evident in other capabilitarian theoretical applications (Kuklys; Robeyns, 2005, p. 10-12; Sen, 1985, p. 9). This also draws attention to the need for advancement in weighting capabilities within the accessibility context to enable accounting for fairness in a broader view of individuals' needs.

2.4.2 Measuring criteria

Based on the discussion in the previous section, we present theoretical criteria to guide the development of accessibility indicators as metrics for CA on transportation based on Equation 1, as previous studies did for accessibility measures in general (Geurs; Wee, van, 2004; Miller, 2018). This is not an exhaustive list but offers a basic standard to examine how accessibility measures can reflect the theoretical features of CA, as well as Rawls' theory of justice, and how to adapt existing measures to account for it.

Previous studies have discussed the connection between accessibility metrics and justice theories (Martens; Golub, 2012; Neutens *et al.*, 2010). However, our study takes a more specific approach by proposing direct criteria to account for CA and Rawls' theory in accessibility metrics, and also discusses operational issues related to this.

2.4.2.1 About objectivity

According to Anderson (2010), there are two types of justice metrics: subjective and objective. Subjective metrics define justice measures by considering factors such as happiness, perceptions, and preferences. Otherwise, objective metrics measure justice in terms of the objective state of individuals such as resources, capabilities, and functionings. The author

states that both capability and resource theorists such as Rawls argue that objective metrics are the most appropriate.

The adaptive preference phenomenon is a problem associated with subjective measures and refers to the tendency of individuals to adapt to their deprivations and settle for less (Anderson, 2010; Sen, 2011, p. 283-284). For instance, owing to adaptive preferences, subjective measures may fail to recognise the negative effects of racism on individuals' well-being. This is because individuals may have adapted to structural and institutional racism (Robeyns, 2017, p. 130-131).

Individuals may perceive their accessibility levels as sufficient, even though they are significantly lower than others who report the same level of satisfaction with their capabilities (Ryan; Pereira, 2021). Therefore, if policy assessment is based on subjective measures, we may end up perpetuating social disparities rooted in people's perceptions. Despite criticism, adaptive preference bias persists in capability research because studies continue to rely on subjective information to measure capabilities (Comim, 2008, p.173).

Adaptive preferences have a greater impact on disadvantaged individuals and endorse deprived situations. Therefore, a better representation of accessibility-as-capability should consider preferences and subjective factors only in the individuals' choices. This approach is consistent with the theoretical representations of the CA literature, according to Robeyns (2003, 2005); however, it differs from what is advocated for general accessibility measures that incorporate these factors (Geurs; Wee, van, 2004; Miller, 2018).

We argue that one of the main differences between criteria for a general accessibility measure and an accessibility-as-capability measure is objectivity. This differs from the work of Vecchio and Martens (2021), who argue for perceived accessibility measures in CA applications. This subjective characteristic of accessibility measures also makes comparisons between people and groups a challenging task, making claims of justice difficult to assert (Miller, 2018). In this context, Martens and Golub (2012) argue that utility-based accessibility measures are inappropriate for addressing justice concerns.

How can we set a poverty line for utility-based accessibility measures, such as the logsum, or based on perceptions? Should the line for wealthy individuals be set “higher” than that for poor individuals given that they are harder to please? How can budget constraints and conversion factors be accounted for, based on preferences? How well individuals must perceive their own accessibility for the transport system to be considered fair?

While Miller (2018) assumes that accessibility varies among individuals owing to their preferences and capabilities, accessibility-as-capability measures should focus only on the

latter. In this regard, it's important not to confuse objectivity in accessibility-as-capability measurement with the exclusion of public participation and perceptions in the transportation planning process.

Engaging in public debate is an essential element of CA as a way to promote consensus building within the society (Comim, 2008, p. 184). This does not imply that justice metrics should accommodate personal preferences, but rather consider the factors that "citizens need to satisfy their objective interests as citizens" in a reasonable way (Anderson, 2010; Comim, 2008, p. 184).

Measures that incorporate perceptions, however, could play the role of identifying critical factors and unmet needs that may be missing in capabilitarian measures (Ryan; Pereira, 2021). For instance, if an objective improvement is made to accessibility-as-capability through a fare reduction, but perceived accessibility remains unchanged, this could signal the presence of missing factors such as public safety concerns or transport service quality issues in our accessibility-as-capability measures. These factors may outweigh the benefits of fare improvements and must therefore be considered in measures and policies.

Gravity-based measures can also lead to underestimation of inequality. These measures often assume that people's mobility reflects their willingness to travel, implying that this is a matter of choice (Giannotti, Tomasiello; Bittencourt, 2022). However, this overlooks the fact that many individuals have limited options and face various constraints, making their mobility more a result of circumstances than choice (Giannotti, Tomasiello; Bittencourt, 2022).

Comim (2008) highlighted that people sometimes confront "tragic choices". For instance, individuals may face the dilemma of choosing between travelling long distances to work and having the income to afford food, or refraining from travel and experiencing poverty and hunger. When we rely solely on travel behaviour data for our accessibility analysis, we overlook the tragic choices encountered by less advantaged individuals. This can be seen as another facet of the adaptive preference problem, which is also present in gravity-based measures.

It's not our intention with this discussion around objectivity to criticise all accessibility measures but rather provide a rational pathway to better analyse the underlying assumptions when develop accessibility-as-capability measures.

2.4.2.2 About publicity

Geurs and van Wee (2004) defined operationalisation as a criterion for accessibility measures, referring to ease of use in practice. The authors also argued that interpretability and

communicability are required for accessibility measures. These questions, however, are not merely a demand of planning practice and accessibility theory, but also a demand of justice.

An important notion of Rawls' theory is the concept of publicity (Rawls, 1999, p. 115), which can be understood in simple terms as transparency. According to Robeyns (2013, p. 460), the publicity criterion "stipulates that the conception of justice must be public and the necessary information to make a claim of injustice must be verifiable by all, and easily accessible".

While Rawls does not consider that capabilitarian measures meet the criterion of publicity, especially due to operationalisation challenges, capability theorists hold a contrasting view. They argue that the objective nature of the capability approach makes it more suitable as a public comparison standard for claims of justice (Anderson, 2010; Robeyns, 2018).

Geurs and van Wee (2004) also argued that accessibility measures should be intelligible to researchers, planners, and policymakers. From a justice perspective, these measures must also be minimally understandable to the public to make it easier for people to perceive their conditions of deprivation and participate in the public debate. It is difficult to imagine planners and policymakers using measures such as space-time prism volume or utility-based measures to make claims of justice in a public debate. However, Arneson (2010) contends that relaxing the publicity criterion is acceptable if it promotes fairness goals more effectively.

Regarding fairness promotion, from the egalitarian and sufficientarian perspectives defended by Pereira et al. (2017) for accessibility, utility measures may not be more effective than other measures. On the other hand, measures such as space-time prism volume add objectivity by considering the time budget and may align more with a sufficientarian view.

The literature underscores the trade-off between complexity and interpretation when measuring accessibility (Geurs; Wee, van, 2004; Miller, 2018). However, we argue that real concerns may revolve around the trade-off between objectivity and publicity. While these two trade-offs are interconnected, they have distinct implications for accessibility. For example, utility-based measures introduce complexity but do not enhance objectivity.

In this sense, we emphasise that an accessibility measure that is more easily understood by the public is closer to being a suitable measure of justice, as the publicity of a measure makes it more effective in promoting fairness and equity. In this sense, when developing accessibility measures for justice assessment, it is imperative to be primarily concerned with the ease of public understanding, as this helps enhance the legitimacy of the evaluation process.

While there are some challenges in accessibility-as-capability measures operationalisation, we highlight that it is not impractical. The successful operationalisation of these measures depends on the careful development of data processing, data collection, and the measures themselves, which should be aligned with the specific scope and objectives of the analysis. Thus, there is a lack of literature on adapting accessibility measures and proposing data treatment processes to meet the demands of the capability approach. Further discussion on this topic is provided in Section 2.4.3.

2.4.2.3 About the level of aggregation

Defining the level of aggregation is one of the requirements of CA application, which encompasses both intrapersonal and interpersonal aggregation issues (Robeyns, 2006). Intrapersonal aggregation refers to the aforementioned weighting problem and refers to how combining capabilities to create an overall measure and how these capabilities must be traded off against each other (Robeyns, 2006). Interpersonal aggregation, otherwise, refers to the settlement of the unit of analysis as individuals or groups of individuals aggregated by spatial or common social features.

According to Robeyns (2008, p. 409), when it comes to interpersonal aggregation, CA empirical applications have been conducted in an aggregated manner. It is assumed that aggregated differences mirror the capability variations of individuals. Despite its usefulness as a source of information on group differences in terms of capability or functioning level, this approach is limited because it does not provide proper information on individuals' capabilities.

Assessments that rely on aggregated data tend to ignore the differences between people, and thus underestimate inequality and poverty. Therefore, a measure that considers individual heterogeneities offers a more suitable assessment of accessibility as a justice metric (Neutens *et al.*, 2010; Vecchio, 2020). In areas with high inequality, such as developing countries, employing average statistics as justice parameters is unreliable because the aggregation process removes important data features (Comim, 2008, p. 182). An important example is income.

Using more aggregated data, such as the average income of zones, to evaluate accessibility is common practice in many studies. However, this approach assumes that all the individuals within each zone face the same budget constraints, which are generally inaccurate. However, disposable income can vary significantly even among family members (Kuklys, 2005). Therefore, relying solely on aggregated data can result in misleading information regarding individuals' accessibility. The practice of drawing conclusions about individuals

based on aggregated data is known as ecological fallacy and has been pointed out as a problem in accessibility assessment in the transport literature (Pereira, 2019; Pereira, Schwanen; Banister, 2017).

As a result, a growing body of transport justice literature has advocated person-centred evaluation (Deka, 2022; Fransen; Farber, 2019; Vecchio, 2020; Vecchio, Tiznado-Aitken; Hurtubia, 2020). To understand the accessibility challenges faced by individuals, including the conversion factors imposed, it is essential to develop disaggregated evaluations and measures (Pereira, Schwanen; Banister, 2017; Vecchio; Martens, 2021).

2.4.2.4 About access

The essence of what we argue to be a capabilitarian perspective on access can be represented by two fundamental questions: "What individuals really can do and be? What activities could they really participate in if they wanted?". While Miller (2018) defines accessibility as a “measure of the potential to interact”, we argue that accessibility-as-capability aligns more closely with conceptions present in the literature related to the freedom of effective participation in activities (Geurs; Wee, van, 2004).

In this context, the principal issue remains on the elements – resources and conversion factors – that generate heterogeneities in individuals’ freedom and, consequently, in their accessibility. These factors, particularly those that limit access, play a crucial role in shaping inequality in accessibility. While there is extensive literature on accessibility and CA regarding factors limiting people's access (Comim, 2008; Cooke *et al.*, 2022; Deka, 2022; Geurs; Wee, van, 2004; Pereira, Schwanen; Banister, 2017), this section aims to bridge the CA and accessibility literature to highlight some of the key needs for measurement improvement by access considerations. To structure the discussion, we used job accessibility as an illustrative example.

First, as discussed in Section 2.3, the monetary component is one of the primary resources to accessibility-as-capability measures to any type of activity. Measures that do not account for monetary aspects in relation to individuals’ income and affordability cannot offer a comprehensive view of access and justice. Even in scenarios with free-fare programs for public transport, the monetary component remains significant, as it affects access to other modes, including individual ones.

To comprehensively account for the impact of affordability on access, it is not sufficient to solely consider individuals' budgets; we must also account for the disparities in costs that individuals face. Fare policies could encompass various differentiations, such as

student discounts, employer-sponsored transit programs, and freedom pass programs for older persons. These policies result in varying costs for individuals depending on their personal characteristics. These disparities significantly influence our perspective on inequality and poverty and highlight the importance of disaggregated analysis to accessibility-as-capability measures.

Another crucial aspect is the conversion factors that influence access to each specific type of activity. For job accessibility, applications commonly disregard educational prerequisites. Education plays a fundamental role in accessing job opportunities in most societies and should not be overlooked. Neglecting education in job accessibility assessments presupposes that individuals who may never have access to education enjoy the same accessibility to employment as individuals with higher education. This overestimates accessibility, especially for the least advantaged, since education level is directly correlated with income.

When assessing group-based differences in accessibility, understanding the contributing factors is vital for incorporating them into the measures. In CA, feminist perspectives highlight how gender roles affect women's employment capabilities (Robeyns, 2008a, p. 91). One shared example in both the CA and accessibility literature is the role of access to childcare facilities in facilitating women's job access (Kawabata, 2014; Robeyns, 2008a, p. 91). In many societies, mothers are expected to bear primary childcare responsibilities. This expectation can be understood as a social conversion factor.

Providing childcare facilities can significantly enhance women's job accessibility, particularly when evaluating gender inequality. In such cases, provide public resources - i.e., public childcare facilities - can counteract societal expectations about women (conversion factor), effectively boosting women’s available time and improving job accessibility. This is a complex issue to formulate from a CA perspective, but given its importance, accessibility literature should address this gap.

Some capabilities are only accessible to individuals if others do not wish to pursue or attain the same capability (Robeyns, 2006). This applies to various factors related to competition in the accessibility literature, from household responsibilities to job demand. Network congestion is another example: when many individuals choose to travel by car, those using buses face reduced access owing to competition for the same network. This also illustrates the intersection of CA with accessibility theory, and how diverse factors can affect access from a capabilitarian perspective.

It is also crucial to recognise factors beyond the traditional components of accessibility, such as land use and transportation. Numerous other factors can significantly limit access. Public safety can be a major barrier to accessibility in certain areas and communities, particularly for women. Additionally, certain types of employment exhibit significant disparities in access between racial groups, with one group facing more impediments. This discrepancy is observable even in prestigious positions, such as Supreme Court seats, in countries like Brazil and the US.

The accessibility literature should continue to make progressive advancements in each of these topics. This highlights the extensive journey ahead in the development of accessibility-as-capability measures, as there is an almost limitless array of conversion factors that can affect access.

2.4.3 Practical strategies

The number of empirical applications of CA on transport is still limited owing to the challenges in operationalising it (Banister, 2019). To facilitate the initial steps in this direction using the proposed framework, we outlined potential strategies, focusing on job accessibility as an illustrative case.

a) Identifying critical factors: Initial efforts to integrate CA into accessibility should focus on the key determinants of each activity type (p), as proposed by Robeyns (2008b, p. 409) to general CA applications. Educational level is a critical factor for job accessibility. Income, representing the monetary budget, is a fundamental resource in most cases that shapes access to transportation modes.

b) Data: To address the level of aggregation, individual-level microdata from publicly available sources, such as census data and mobility plans, can be used. These sources commonly contain information on income and educational levels and can be expanded using methods such as spatial microsimulation (Ballas *et al.*, 2013; O'Donoghue *et al.*, 2013). This approach not only aids in addressing aggregation concerns, but also promotes publicity, as these datasets are available in many locations.

c) Accessibility formulation: Adapting established measures such as COM measures can incorporate individual characteristics (Geurs; Wee, van, 2004), including income, as opposed to relying on average income as often done (Bocarejo; Oviedo, 2012; Guzman; Oviedo, 2018). Furthermore, time, income, and educational constraints can be integrated as binary functions, ensuring that individuals have

access to job opportunities if they meet criteria, such as travel time thresholds, affordability thresholds, and educational prerequisites. This approach offers a more nuanced understanding of individual disparities including inequalities and poverty.

d) To advance specific inequality topics, surveys are needed. For instance, the analysis of women's job accessibility concerning childcare necessitates consideration of multiple factors. Surveys should encompass disposable time, childcare responsibilities, access to childcare facilities and disposable income.

In this case, in addition to binary functions related to travel time thresholds, affordability thresholds, and educational prerequisites, COM measures should encompass disposable time to work. In this context, with a simplified view, women will have access to job opportunities if one of the following conditions is met: i) the woman possesses enough disposable time to engage in work; or ii) the woman lacks sufficient time for work because it takes care of children but has disposable income to cover childcare facility expenses or has access to public childcare facilities.

It is crucial to recognise that these examples represent simplifications, and additional factors warrant discussion and inclusion. Nonetheless, these illustrative cases demonstrate several key points in these examples: i) they adhere to objectivity criteria through the utilisation of binary functions, ensuring clear and consistent measurement; ii) they fulfil publicity criteria by employing easily understandable measures and criteria, along with data types that are readily accessible; iii) they consider individual constraints and characteristics, addressing the level of aggregation needed for a nuanced assessment; and iv) they directly account for access issues relevant to each specific case, ensuring a more accurate analysis.

By adopting these strategies, transportation studies can embark on a path to creating more comprehensive accessibility measures grounded in the CA, contributing to a deeper understanding of equity and justice in transportation systems.

2.5 Conclusions

The framework presented in this article advances in the dialogue between CA and Rawls theory on accessibility measurement by formally specify a framework to accessibility-as-capability measure development, what was not yet presented in the literature. Are individuals truly able to engage in certain activities? Are low-income individuals deprived of access to opportunities? Is there gender inequality? Our framework aims to assist in the development of accessibility measures that account for the factors to answer these questions.

In addition to the argument of Randal et al. (2020), which focuses on transport policies, we argue here that the next step in applying capability theory to transportation policies should initially be to understand the broad range of conversion factors that impact accessibility, especially related to individual and social constraints, as argued by Robeyns (2008, p. 409). Thus, it is possible to better understand which population groups and individuals are deprived, and how policies affect their capabilities. This will help formulate transport policies that create a more appropriate environment for justice claims and contribute to broader consideration of concerns about social exclusion.

By the understanding that the housing possibilities for individuals can be incorporated into accessibility as land-use resources, our framework also supports future studies that explore how people's location options affect accessibility. This could produce accessibility measures that include all places where people can afford and live – their housing options–based on their monetary constraints and conversion factors, instead of just their current location, which could be a result of their preferences. This capability perspective on housing and accessibility could help advance claims of justice in transportation assessment.

Further studies could also build a theoretical exploration of existing accessibility measures, based on the framework proposed in this study. This will help to complement or create novel measures to accessibility-as-capability applications. This opens a gap in empirical applications of accessibility assessment based on the capabilitarian view proposed as a way to analyse the effect of elements such as the monetary budget and other constraints on equity and sufficiency evaluations. This could help understand how the current accessibility analysis underestimates inequality and poverty.

Although some of the frameworks reviewed propose a broad capability approach application to transport, none of them address the weighting problem, also called intrapersonal aggregation, despite the existence of empirical efforts in transport (Azmoodeh, Haghighi; Motieyan, 2023). According to Robeyns (2006), one of the theoretical specifications needed to make a complete CA application is to define whether a trade-off between capabilities is necessary and the weight of each one. Accessibility is a complex concept encompassing a wide range of capabilities. Accessibility to work, education, and leisure are commonly used measures, and each one is a different capability. Miller (2018) called this ‘hyperspace’ of accessibilities.

For example, if a deprived group of individuals has little access to education and jobs, which one must be treated first? Should we build a new school in this area or invest in public transport? This is also called the tragic choice problem (Robeyns, 2018), and addressing

the weighting issue on accessibility is crucial to solve this problem and for the development of a complete theory of justice in transport and represents an important avenue for future research.

3 ACCESSIBILITY INEQUALITY AND DEPRIVATION DUE TO INDIVIDUALS' CONSTRAINTS: AN APPLICATION OF THE CAPABILITY APPROACH

3.1 Introduction

Accessibility plays a crucial role in transport justice assessment in both inequality and poverty aspects, offering a comprehensive perspective on individual freedoms to activity participation (Martens, 2016; Pereira; Karner, 2021; Pereira, Schwanen; Banister, 2017). In the realm of distributive justice, the understanding of freedom as the real potential of individuals aligns closely with the Capability Approach (CA) conceptualizations (Robeyns, 2003). CA can be understood as a multipurpose framework to address justice concerns focused on individuals' real opportunities (Robeyns, 2017b).

The confluence of CA and accessibility has been endorsed in transport justice literature, contending that accessibility can offer a more nuanced representation of capabilities and justice, ultimately leading to the arise of the concept of accessibility as a capability (Cao; Hickman, 2019; Chen; Akar, 2017; Deka, 2022; Nahmias-Biran, Martens; Shiftan, 2017; Pereira, Schwanen; Banister, 2017; Randal *et al.*, 2020; Vecchio, 2020; Vecchio; Martens, 2021). However, a few of them have made progress in suggesting accessibility metrics from a CA perspective (Deka, 2022).

This lack of studies could be related to the fact that CA applications in the transport justice literature advocate person-centred evaluations of accessibility (Deka, 2022; Fransen; Farber, 2019; Vecchio, 2020; Vecchio, Tiznado-Aitken; Hurtubia, 2020). These studies often focus on small-scale surveys (Deka, 2022; Ryan; Pereira, 2021), which, despite displaying important empirical evidence, cannot provide a broader perspective on urban reality. None of them, therefore, provide practical solutions for overcoming the operational issues required to enable individuals' assessments on a large scale, such as across an entire city.

Measures that consider individuals' heterogeneities provide a more complete view of accessibility to justice assessments (Neutens *et al.*, 2010; Vecchio, 2020). Accounting for these heterogeneities is also crucial for comprehensively understanding the inequality and poverty conditions faced by people (Vecchio; Martens, 2021).

Several factors can lead to inequality and poverty in accessibility, such as economic, geographical, physical, and temporal individual constraints (Luz; Portugal, 2022). However,

accessibility studies often focus primarily on travel time costs and neglect other factors that limit access (Vecchio; Martens, 2021).

In the capability literature, Sen (1999, p. 87) argues that income is “one of the major causes of poverty”, which is a key factor limiting capabilities. Many studies on accessibility have highlighted how income restrict accessibility, by depriving individuals of access to transport modes due to affordability issues (Bocarejo; Oviedo, 2012; Falavigna; Hernandez, 2016; Guzman; Oviedo, 2018; Luz; Portugal, 2022).

Despite this, most accessibility measures either overlook affordability or propose its integration in an aggregated manner, disregarding its individual aspects (Bocarejo; Oviedo, 2012; Gómez-Lobo, 2011; Guzman; Oviedo, 2018). Herszenhut *et al.*(2022) highlighted that overlooking the monetary aspect on accessibility could led to biased evaluations on transport justice, overestimating accessibility to the most vulnerable people. Furthermore, the authors indicated the need for studies that examine affordability on accessibility considering the population income distribution, which remains a gap.

Examining accessibility to specific activities reveal additional constraining elements. For instance, some leisure activities may be limited to individuals with physical aptitude. In the context of job-related accessibility, educational prerequisites emerge as compelling limiting factors, especially for individuals lacking formal education. CA literature designates these factors as “conversion factors”, which interfere with people’s genuine capabilities (Robeyns, 2003). Therefore, it is imperative to incorporate these factors into accessibility measures to provide better estimates of accessibility as a capability.

The aim of the present study is to propose an accessibility-as-capability measuring method to better capture inequality and poverty in the accessibility domain. This method provides a two-fold main advance compared to previous studies. First, we propose an accessibility-as-capability measure by building an adaptation of cumulative opportunity measures that accounts for individuals’ heterogeneities and conversion factors. Second, we propose a solution to the issue concerning the limited availability of individual-level data for accessibility-as-capability applications, thus enabling large-scale studies.

The proposed metric and data modelling approach were demonstrated through a case study in Fortaleza, a Latin American city located in Brazil. This application illustrates the advances and implications of the method proposed in this study for equity and poverty assessments related to accessibility measurements.

3.2 The capability approach on accessibility

The capability approach advocates that justice assessment should focus on individuals' real opportunities – the capabilities (Deka, 2022; Robeyns, 2005; Sen, 1995, p.81). Within the realm of transport literature, an expanding body of literature highlights a profound relation between capabilities and accessibility (Cao; Hickman, 2019; Chen; Akar, 2017; Deka, 2022; Nahmias-Biran, Martens; Shiftan, 2017; Pereira, Schwanen; Banister, 2017; Randal *et al.*, 2020; Vecchio, 2020; Vecchio; Martens, 2021). These studies champion the notion of accessibility as a capability, establishing it as a central variable in the assessment of transport justice.

CA theory embodies some fundamental concepts (Robeyns, 2005; Vecchio; Martens, 2021). In the accessibility context, we highlight the following.

a) Resources, which refer to the "means to achieve", or capabilities inputs, such as income, time, goods (e.g., cars, bicycles, shoes), and services (e.g., transit, taxi, shared transport), frequently acting as "prerequisites" to access. For instance, individuals need to spend their resources, such as time and money, to access an activity.
b) Conversion factors, which delineate how people can transform resources into capabilities, can be categorised as personal (e.g., age and gender), social (e.g., fare policies, discrimination), and environmental factors (e.g., built environment) (Pereira, Schwanen; Banister, 2017; Robeyns, 2005; Vecchio; Martens, 2021). These factors can reinforce or diminish an individual's capabilities. For instance, a fare discount policy for students makes public transport more affordable for low-income people, thereby improving their accessibility.
c) Capabilities are the most important concept within CA. Capabilities are the real freedom available to individuals, comprising their set of choices (Robeyns, 2005). In the transport context, the accessibility-as-capability of an individual could be understood as the set of opportunities that the individual could access and participate in if he wants it (Cooke *et al.*, 2022; Pereira, Rafael *et al.*, 2019; Robeyns, 2017b, 2018; Vecchio; Martens, 2021).

To discuss about accessibility-as-capability, there is a crucial question: Which opportunities are really available to an individual? What can they access? In a capabilitarian

perspective, the response is - depends on his resources, especially income, and conversion factors. We could start arguing about resources.

Income has a unique significance within the resources of capabilities. CA literature underscored income as a compelling determinant of capability deprivation (Sen, 1999, p. 87), which is not different in the accessibility domain (Guzman; Oviedo, 2018; Urry, 2007, p. 191). In recent years, the impact of income on accessibility has gained attention in transport planning literature, despite the existence of few works accounting directly by this on accessibility measures (Bocarejo; Oviedo, 2012; El-Geneidy *et al.*, 2016; Herszenhut *et al.*, 2022).

However, since the conversion of resources, such as income, determines capabilities in a broad term, it holds true in the accessibility context - the conversion of income is an accessibility determinant. Income limits access to mode options owing to travel costs; nonetheless, these costs can vary according to individual and societal aspects. As exemplified before, with student discount policies (a social conversion factor), students have an improvement in their accessibility, especially if they are low-income.

Although some studies have incorporated monetary costs into accessibility measures (Bocarejo; Oviedo, 2012; El-Geneidy *et al.*, 2016; Guzman; Oviedo, 2018; Herszenhut *et al.*, 2022), none have directly accounted for the wide spectrum of the different costs imposed by fare policies on individuals. These costs vary among individuals owing to factors such as student discounts, employer-sponsored programs, and free older persons' pass programs. Thus, by not considering the role of conversion factors in costs, these studies may overlook important aspects of individual heterogeneity in access.

Conversion factors also delimitate the activities available to individuals. For instance, to perform job activities, individuals must meet certain prerequisites, such as legal working age, a social conversion factor, and educational requirements, which relate to a personal conversion factor – educational level (Robeyns, 2003; Vecchio; Martens, 2021).

Measures that recognise individuals' heterogeneities offer a more suitable standpoint regarding accessibility as a metric of justice (Neutens *et al.*, 2010). Therefore, person-centred evaluations are gaining advocacy in the transport literature (Deka, 2022; Fransen; Farber, 2019; Vecchio, 2020; Vecchio, Tiznado-Aitken; Hurtubia, 2020). Developing disaggregated measuring methods is paramount for comprehending individual accessibility challenges and justice issues in transportation (Neutens *et al.*, 2010; Pereira, Schwanen; Banister, 2017; Vecchio; Martens, 2021).

Nevertheless, justice assessments require more than disaggregation. Anderson (2010) argued for the primacy of objective metrics over subjective measures, as the latter

hinders comparisons among individuals and groups (Miller, 2018) and are more vulnerable to adaptive preference bias (Comim, 2008, p. 173). Therefore, metrics such as utility-based measures are unsuitable for justice assessment (Martens; Golub, 2012).

Accessibility measures, in addition to previous discussions, must also meet the publicity criteria. Publicity is a justice assessment demand that, in simple terms, regards the need for transparency and clarity on information necessary to make a claim of justice (Robeyns, 2013, p. 460). This aligns with Geurs and van Wee (2004) advocacy by operationalisation and interpretability of accessibility measures, but goes beyond: publicity demand metrics to be intelligible to the general populace, as a means to enable individuals to participate in the public debate.

3.3 Proposed accessibility-as-capability measure

Drawing from previous capability formulations in the CA literature (Kuklys; Robeyns, 2005, p. 10-12; Sen, 1985, p. 9), a general measure of accessibility-as-capability is presented in Equation 3. $\boldsymbol{A_i}$ represents the set of accessibility-as-capabilities for individual *i*, that could consider each type of activities or purposes "*p"* (e.g., job, education, and leisure activities). This capability set is restricted by the resources $\boldsymbol{x_i}$ available to the individual *i* (e.g., income and transport modes), and by the range of conversion factors, $\boldsymbol{z_i}$ (e.g., fare policy and physical capacity). The individual conversion function, f_{ip}, can be understood as the accessibility measure function, representing the conversion of resources of the individual *i* into capabilities through the application of the conversion factors, relating to activities of type *p*. This formulation can be used as a starting point for adapting well-known accessibility measures to the capability context.

$$\boldsymbol{A}_i = \left\{ f_{ip}\left(\boldsymbol{x_i}, \boldsymbol{z_i}\right); p \in \mathbf{P} \right\} \tag{3}$$

The present work proposes adapting the cumulative opportunities measure (COM) to build a new accessibility-as-capability measure. We chose COM as a basis for the measure for the following reasons: i) it addresses publicity, in terms of ease of operationalisation and understanding by people, what is critical to give conditions to public debate participation; ii) it meets the objective criterion, by providing results with practical meaning and by using binary functions to address travel time and cost impedances, facilitating the public debate about distributive justice on accessibility; iii) despite being a location-based measure, it allows the

inclusion of individual characteristics, making it possible to assess accessibility at the individual level (Geurs; Wee, van, 2004); and finally, it is a type of measure already used for affordability studies on accessibility (Bittencourt; Giannotti, 2021; Herszenhut *et al.*, 2022).

Equation 4 presents the proposed accessibility-as-capability measure which quantifies the maximum number of opportunities that an individual can access, constrained by his monetary budget and conversion factors. Formally, the proposed accessibility measure quantifies for each individual *i*, the maximum number of activities of type *p* that can be accessed using all available transportation modes $\boldsymbol{M_i}$ that are financially feasible for individual *i* within his budget b_i during a specified time period, while considering a set of conversion factors. To account for the affordability issue in a more complete view, this maximisation is performed by considering both the available budget and the planned number of round trips *D* within the specified time frame.

$$Ac_{i,p}(\boldsymbol{x_i}, \boldsymbol{z_i}) = \ Maximize \sum_{d=1}^{D} \frac{\sum_{j=1}^{n}(\boldsymbol{a_{p,j}}|\boldsymbol{z_i}) \ \max_{m \in M_i} \left(f\left(\boldsymbol{t_{i,j}}|\boldsymbol{z_i}\right) f\left(\boldsymbol{c_{i,j}}|\boldsymbol{z_i}, \ b_{i,d}\right)\right)}{D} \quad (4)$$

Restricted to:

$$\sum_{d=1}^{D} b_{i,d} \ \leq \ b_i \ | \ b_{i,d} \geq 0 \quad (5)$$

Where:

$Ac_{i,p}$is the measure of accessibility-as-capability of individual *i* to activities of type *p* (e.g., jobs, education, healthcare);

x_i is the set of resources - budget set, transport, land use, and time;

$f(.)$ are the individual conversion functions, or impedance functions, which depend on the set of conversion factors z_i of individual *i* (individual, social, and environmental factors);

$a_{p,j}|z_i$ is the number of activities *a* of a specific type *p* located in *j*, conditioned by the conversion factors z_i of individual *i*;

$\boldsymbol{c_{i,j}}|\boldsymbol{z_i}$ is the set of monetary travel costs, considering each mode $m \in M_i$, between the origin of individual *i* and destination *j*, conditioned by the individual conversion factors z_i (e.g.: relative to fare policy);

$\boldsymbol{t_{i,j}|z_i}$ is the set of travel times, considering each mode $m \in M_i$, between the origin of individual i and destination j, conditioned by the individual conversion factors z_i (e.g.: relative walking speed);

D is the number of potential round trips during the analysis period. We suggest setting this timeframe to one month to be consistent with the affordability analysis;

$b_{i,d}$ is the monetary budget of individual i for each round trip d (e.g., one round-trip by day).

Where the resources x_i are:

$$x_i = \{b_i, \boldsymbol{M_i}, T, \boldsymbol{A}\} \tag{6}$$

b_i is the monetary budget of individual i. We recommend setting this value as a percentage of individual's disposable income;

M_i is the set of modes or transport services available to individual i;

T is the individual time budget (time threshold), which is usually considered the same for all individuals in COM measures;

A is the set of all activities $a_{p,j}$ in the geographical area analyzed.

Where the conversion factors z_i, of each individual i, are:

$$z_i = \{pf_i, sf_i, ef_i\} \tag{7}$$

pf_i are personal conversion factors, such as age and educational level.

sf_i are social conversion factors, such as fare policy and legal working age.

ef_i are environmental conversion factors, such as the built environment and road networks.

The formulation considers a binary cost and affordability impedance function, conditioned by conversion factors, as follows:

$$f\left(\boldsymbol{c_{i,j}}|\boldsymbol{z_i}, b_{i,d}\right) = \begin{cases} 1, & \forall\, c_{i,j,m} \in \boldsymbol{c_{i,j}}|\, \boldsymbol{z_i} \leq b_{i,d}, by\ each\ mode\ m \in M_i \\ & considering\ z_i\ effects\ on\ travel\ cost \\ 0, & otherwise \end{cases} \tag{8}$$

The travel time impedance function is given by:

$$f(\boldsymbol{t_{i,j}}|\boldsymbol{z}_i) = \begin{cases} 1, & \forall\, t_{i,j,m} \in \boldsymbol{t_{i,j}}|\boldsymbol{z}_i \leq T, by\ each\ mode\ m \in M_i \\ & considering\ z_i\ effects\ on\ travel\ time \\ 0, & otherwise \end{cases} \quad (9)$$

The argumentation regarding Equation 4 assumes that individuals have a monthly budget b_i which is allocated across the period to cover the considered number of round trips *D*. This allocation results in budget values $b_{i,d}$ for each potential round trip. For each of these round trips, we calculate the accessibility of individuals, considering their budget $b_{i,d}$ and the time threshold T.

Therefore, for each round trip we calculate the number of activities that an individual can access within the time threshold T when the travel cost can be afforded by the budget $b_{i,d}$. The overall accessibility measure considered is the maximum average accessibility across all round trips *D*, been calculated by optimising the allocation of budgets $b_{i,d}$ restricted to the limit of (monthly) budget b_i. This optimisation is necessary due to the non-linear relationship between daily budget and opportunities, particularly given the distinct cost functions inherent in each mode.

This optimisation approach offers a more objective perspective on people's potential participation in activities, considering their monetary budget. This is seen as an effective way to estimate their actual capabilities, advancing the literature by considering restrictions at the individual level, as well as the financial budget to afford round trips to access activities for a given period (e.g., the number of workdays within a month). Therefore, this approach is more sensitive to monetary budget variations, offering a more comprehensive view than conventional analysis, which typically considers only a typical one-way trip in aggregated models. With this, for instance, we are capable of distinguishing in accessibility estimates between individuals that can pay just for one round trip and individuals that can pay for ten roundtrips.

Furthermore, it is essential to emphasise that our approach consolidates individual accessibility related to various transportation modes into a single measure using the affordability impedance function (Equation 8). With this equation, if any mode presents a travel cost c to the destination that is less than the budget limit $b_{i,d}$ *j*, the activities in *j* are considered accessible to the individual. This multimodal approach comprehensively accounts for affordability, providing a more holistic perspective on individual accessibility rather than focusing on a single mode or just on transit as often done.

Another advancement concerns the consideration of transport cost variations between individuals due to personal and social conversion factors, especially those related to fare policies. This is established by the argument $\boldsymbol{c_{i,j,m}|z_i}$ in Equation 8. For example, students often benefit from fare discount. Therefore, the inclusion of a social conversion factor, represented by the student fare discount policy, along with a personal conversion factor, which is student status, changes the cost considered in the affordability function.

Another important contribution is the role of the conversion factors in Equation 4. The $a_{p,j}|z_i$ argument establishes that individual i can access activities $a_{p,j}$ only if he meets activity prerequisites or related constraints. For example, in Brazil, the minimum working age is 18 years old. Legal restrictions impose a limitation on access for people under 18 years, a social conversion factor, that relates to age, a personal conversion factor. Job activities also have educational level restrictions, which play an important role in formal work accessibility.

The argument $\boldsymbol{t_{i,j}|z_i}$ in Equation 9 indicates that individuals travel times depends on their conversion factors. This argument enable consider, for instance, different walking speeds across individuals, what impacts also in travel times by transit. This enable also account for physical disabilities and other factors.

These methodological improvements in accounting for conversion factors, as well as monetary budgets, can only be accurately considered when data at the individual level are available.

3.4 Study area: Fortaleza, Brazil

This section aims to contextualize populational, spatial, and transport system issues related to the application on the study area. Fortaleza is the capital of Ceará, Brazil. The city has the fourth largest population in the country, and is the capital with the highest population density in Brazil. In terms of income inequality, Fortaleza has a Gini index of about 0.63, making it the 186th city with the greatest inequality in more than 5500 municipalities in one of the most unequal countries in the world.

According to the 2010 Brazilian census, 36.9% of the people in Fortaleza have a per capita income of less than half the minimum wage, and the values adjusted for inflation to 2023 represent an income per capita of less than R$ 546.60, or around $110 American dollars monthly. For them, the basic bus fare in Fortaleza, R$ 4.50 (~$0.91), represents almost 1% of their income. To make a round trip each workday of a month (44 trips), they need at least 36% of their income.

The population in Fortaleza is geographically dispersed, but there is a large concentration of people on the west side of the city, where a substantial proportion of low-income people are concentrated (Figure 1, A). In contrast, job opportunities and high-income individuals tend to cluster around the downtown and central-north areas of the city (Figure 1, B and C). It is worth noting that taxi stands and transit infrastructure are also concentrated in these central areas (Figure 1, D).

The fare structures are listed in Table 1. The bus system (Figure 1, D), including Bus Rapid Transit (BRT), operates on a flat fare structure with a base fare of R$ 4.50 (~$0.91). There was also a discount during the off-peak periods (9:00-11:00 am, 2:00-4:00 pm) and weekends (Saturday and Sunday). Furthermore, there is no limit to transfers in the bus system within a two-hour period after smartcard use. The rail system is composed by three lines (Figure 1, D), including one Light Rail Transit (LRT) line. Each line had a different fare, varying from a line with a free pass (LRT, under assisted operation) to a fare of R$3.60 ($0.72).

The Equation 10 represents the taxi service cost, considering the fare structure stipulated by ETUFOR. The taxi service cost, on the other hand, depends on distance and waiting or stopped time (e.g., at traffic lights). The initial charge is R$ 5.75 ($1.16). In addition, there is a charge of R$ 3.43($0.69) by kilometres travelled, and a charge of R$ 34.2 ($6.88) by stopped hours in service (Equation 10). As we can see, even the initial charge is higher than the fare of bus and rails system, evidencing that the taxi service is not affordable for low-income.

$$F_{ij} = 5.75 + 3.43 * d_{ij} + 34.2 * t_s \quad (10)$$

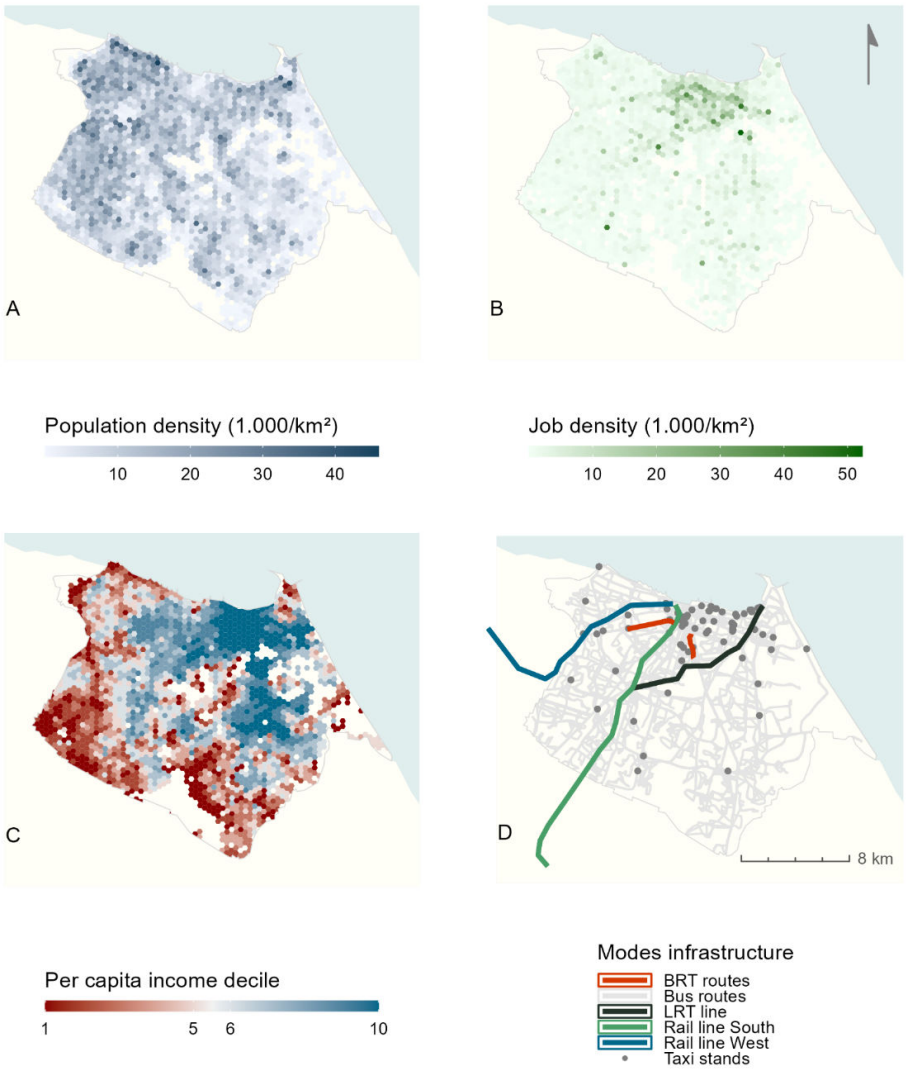
Where:

F_{ij} is the taxi fare from location i to destination j in R$;

d_{ij} is the distance between i and j in kilometres;

t_s is the stopped time during travel in hours.

Figure 1 - Population (A), jobs (B), income (C), and public transport infrastructure (D) distribution in Fortaleza, Brazil.



Source: Author's own elaboration.

Since 1985, Brazil has enacted a national law establishing an employer-sponsored transit programme for formal employees. This program requires employers to subsidise employees' commuting expenses, with a maximum contribution of 6% of the employees' salary towards these costs. In Fortaleza, this program is operationalised through smart cards, providing subsidised public bus transportation to formal employees' work commutes. The city also has a student fare discount policy that guarantees a minimum discount of 50% on fares for the municipal bus transit service. State legislation also guarantees this discount in rail transit services in Fortaleza.

In Fortaleza, there is no fare integration between Bus + Rail services, resulting in two separate fares for trips that require both modes (e.g., bus + LRT line), as shown in Table 1. Workers who are also students benefit from the two policies and have the lowest overall charges for public transport.

Table 1 - Fortaleza's public transport fare structure (values from August 2023)

Modes or trip integration	Fare group			
	General	Student	Formal workers	Formal workers and students
Bus	R$4.50 ($0.91)	R$1.50 ($0.30)	R$ 0.00 ($0.00)*	R$ 0.00 ($0.00)*
Rail line South	R$3.60 ($0.72)	R$1.80 ($0.36)	R$3.60 ($0.72)	R$1.80 ($0.36)
Rail line West	R$1.00 ($0.20)	R$0.50 ($0.10)	R$1.00 ($0.20)	R$0.50 ($0.10)
LRT line	R$ 0.00 ($0.00)**	R$ 0.00 ($0.00)**	R$ 0.00 ($0.00)**	R$ 0.00 ($0.00)**
Bus + Rail line South	R$8.10 ($1.63)	R$3.30 ($0.66)	R$3.60 ($0.72)*	R$1.80 ($0.36)
Bus + Rail line West	R$5.50 ($1.11)	R$2.00 ($0.40)	R$1.00 ($0.20)*	R$0.50 ($0.10)
Bus + LRT line	R$4.50 ($0.91)	R$1.50 ($0.30)	R$ 0.00 ($0.00)*	R$ 0.00 ($0.00)*
Taxi	See Equation 10.			

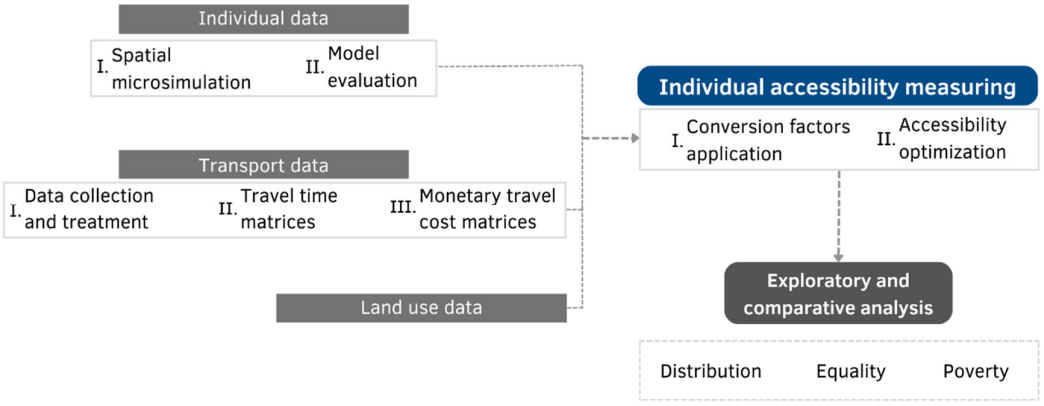
Source: Author's own elaboration.
All values consider only one trip by mode or multiple trips in bus mode within 2 hours.
* Value to contribution in employer-sponsored transit programs to bus transportation is deducted from the salary at origin, corresponding to at most 6% of income in the month.
** Free boarding (assisted operation).

3.5 Application method and data

We applied the proposed indicator to assess accessibility to formal jobs in Fortaleza. The analysis was focused on heads of household individuals due their direct demand and need for job opportunities. This application has a dual focus. Its first objective is to showcase the practical implementation of the proposed accessibility-as-capability measure, and therefore of CA on accessibility domain. We employed a spatial microsimulation model, which is a method commonly used to overcome data scarcity at the individual level (Ballas *et al.*, 2013).

The second objective was to examine the impact of accounting for individual constraints on accessibility. This entails contrasting the proposed measure with diverse variations based on COM measure and analysing the resulting disparities in equality and poverty. The application method is summarised in Figure 2 and discussed in the following sections.

Figure 2 - Method diagram.



Source: Author's own elaboration.

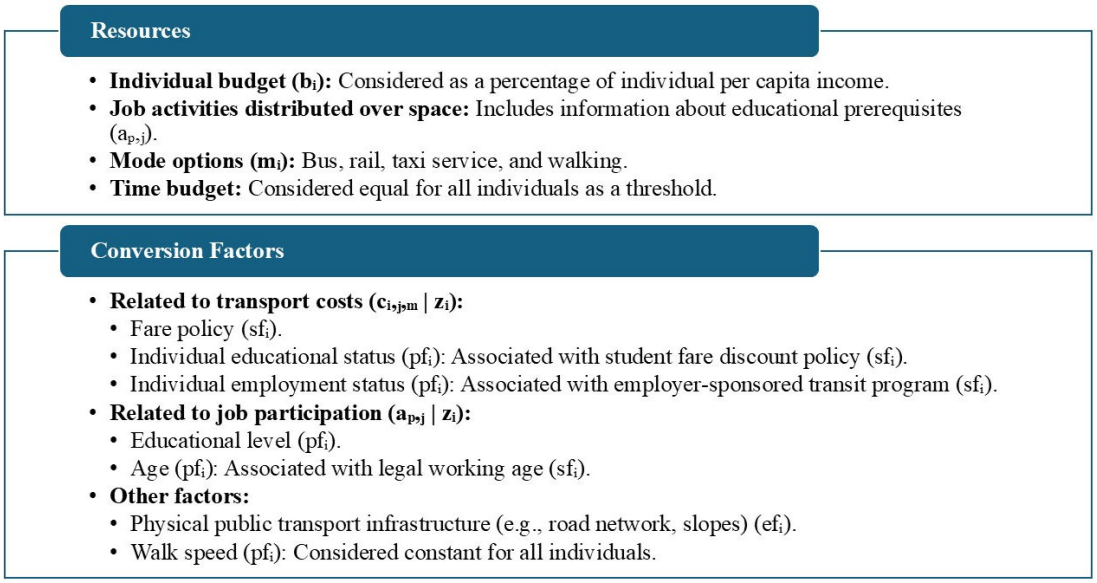
3.5.1 About the application

As previously mentioned, multiple elements can influence access, so it is essential to have parsimony to choose relevant factors on accessibility-as-capability assessments. Given that our application is focused on job accessibility, it is imperative to consider employment-related variables, as well as affordability. The essential affordability variables encompass individual budgets and fare policy scenarios (see Table 1). Educational prerequisites are considered crucial constraints for job participation. A comprehensive list of resources and conversion factors under consideration is presented in Figure 3.

Since this application focused on job accessibility, we considered 22 roundtrips (D) in the analysis, one for each working day in a month. The individual budget (b_i) was considered as a percentage of individuals' household per capita income, understanding that it better represents the disposable income of the heads of households than their direct personal income, due to their financial responsibilities within the household. The adoption of income percentages aligns with established practices of affordability evaluation (Gómez-Lobo, 2011; Yang *et al.*, 2023).

Due to absence of specific data pertaining to individual expenses and disposable income, we explored different budget-threshold scenarios. The World Bank has traditionally suggested that a reasonable transport expenditure is 10% of an individual's income (Armstrong-Wright; Thiriez, 1987). Examining aggregated data from the Brazilian Household Budget Survey in Fortaleza, we find that the maximum expenditure on transport across income classes is 20% of income. Therefore, we considered three thresholds:10%, 15%, and 20% of individual household per capita income.

Figure 3 - Resources and conversion factors considered.



Source: Author's own elaboration.

The heads of households' per capita income were provided by the microsimulated data (see Section 3.5.3). We considered publicly available services, including bus system, rail system, and taxi service, in addition to walking, as mode options (m_i). Incorporating taxi services in this study offers a more comprehensive perspective on the accessibility of wealthier individuals, given the relatively higher expenses associated with this mode of transportation.

We adopted as spatial unit of analysis the regular Uber H3 hexagonal grid commonly used in accessibility studies. Hexagonal grids offer a simpler and more symmetric nearest neighbourhood, eliminating ambiguities that may arise in other spatial aggregations (Birch, Oom; Beecham, 2007). This symmetry is also associated with less bias related to the well-known modifiable areal unit problem (MAUP) on accessibility estimates (Levinson; King, 2020).

We computed the travel time matrices for all origin-destination pairs, encompassing all transportation mode options, employing the r5r open-source R-package for multimodal routing (Pereira *et al.*, 2021). These matrices were estimated to morning period between 7:00-8:00, which is a critical timeframe for job accessibility. For the accessibility estimation, the median travel time within the departure timeframe was considered. It is important to note that, for the taxi mode, the total travel time accounts for the time between the taxi point and the individual's location, as well as the time between the individual's location and destination.

In the absence of individual time budget data, we considered three distinct travel time thresholds: 15 min, 30 min, and 60 min. This approach aligns with prior applications aimed at overcoming the arbitrariness in COM measures (Herszenhut *et al.*, 2022). Some parameters of the application, including the threshold scenarios, are summarised below:

a) Roundtrips considered: 22 roundtrips
b) Maximum percentual expenditure in transport (B): 10%, 15%, and 20% of per capita income (scenarios)
c) Maximum travel time thresholds by motorized modes: 15, 30, and 60 minutes (scenarios)
d) Departure time: 7:00 AM (morning peak)
e) Maximum walking travel time thresholds: 20 minutes
f) Maximum walking time to access and egress the transit network: 20 minutes
g) Walking speed: 3.6 km/h
h) Maximum number of public transport rides allowed in the same trip: 3
i) Stopped time on taxi fare calculation: 30% of travel time

It is important to note that these thresholds were applied exclusively to the travel time from origin to destination without considering the return journey of the roundtrip. In contrast, the travel monetary costs accounted for all round-trip expenses.

To calculate the travel cost matrices, we considered the role of individuals' set of conversion factors $\boldsymbol{z}_i$. As already described in Table 1, by varying studying and working status, individuals face different costs for bus and rail services due to the student fare discount program and employer-sponsored transit program, respectively. We account for this for each individual, also considering mode integration (combined fares on travel using both bus and rail).

To calculate the travel cost by taxi (Equation 10), we also used r5r software to estimate the travel distances between all origin-destination pairs. As data on stopped time for fare calculation were unavailable, we assumed this as a percentage (30 %) of travel time from an individual's location to their destination, which allowed us to make reasonable fare estimates. By considering both travel distances and the estimated stop time, we calculated the travel costs for the taxi mode during the morning peak period (7:00-8:00), and the median cost was used for accessibility estimation.

Accounting for job participation-related conversion factors was a twofold approach. First, we consider only individuals over 18 years old, due to their legal working age, as capable of accessing formal jobs. In addition, we restrict the analysis to people under 65 years old, a reference age for retirement. Second, we considered educational qualifications, whereby individuals were limited by their educational level to access opportunities. Consequently, those

with lower educational levels are limited to low educational job opportunities, whereas individuals with higher educational levels have access to low-, middle-, and high-educational job opportunities.

Despite some existing applications that indirectly consider educational levels in simplified ways (Pereira, 2019; Pereira *et al.*, 2019), in such applications, arbitrary connections are established between average income and education levels. These associations are typically made at more aggregated spatial units, linking a specific average income of an area to a particular educational level for the entire population in that area (e.g., low education level opportunities for people in areas with average income up to the 5th decile) (Pereira, 2019; Pereira *et al.*, 2019). These simplifications are based on two main assumptions. Firstly, the assumption is made that all individuals within a spatial unit have identical income, equivalent to the average income of that location. Secondly, there is an assumption that individuals within a particular income level share the same level of education. This permits the attribution of a specific education level to all individuals within a spatial unit based on the spatial average income. However, these two oversimplifications fail to account for potential heterogeneity among individuals within the same spatial unit and among those with similar income levels. Since prevailing inequality measures on transport justice, such as the Palma ratio (Guzman; Oviedo, 2018; Herszenhut et al., 2022), are estimated based on income and accessibility, these simplifications could completely bias the inequality estimations.

Considering the previous discussion, accessibility was calculated for each individual, accounting for all possible combinations of the time and monetary budget thresholds (Table 2). To solve the maximisation function in Equation 4, it is necessary to use a nonlinear optimisation method. We applied the constrained optimisation by linear approximation (COBYLA) method, which uses simple iterations to determine the optimal solution and does not necessarily lead to a global optimum (Powell, 1994). However, given the simplicity of the objective function and the constraints, this is a reasonable approach.

Table 2 – Accessibility estimation scenarios

Scenario	Time budget (min)	Monetary budget (%)
1	15	10
2	15	15
3	15	20
4	30	10
5	30	15
6	30	20
7	60	10
8	60	15
9	60	20

Source: Author's own elaboration.

3.5.2 Data sources

The proposed application requires several types and sources of data, considering the need for spatial microsimulation and accessibility analysis. To run the microsimulation, three data types were used:1) Brazilian 2010 census microdata, which in Fortaleza have a sample of more than 120.000 individuals, and its geographical distribution in 55 Public Use Microdata Areas (PUMA), each of which has between 32 and 90 census tracts; 2) aggregated Brazilian 2010 census data by census tracts, with number of individuals by different attributes; and 3) statistical grid of 200 × 200 m, which has geographically count of population data by gender.

Census microdata is the source of individual information and provided data about personal and household per capita income for each individual, as well as other attributes such as educational level (e.g., low, mid, high), educational status (i.e., if the individual is currently studying), household position, age, gender, and employment status. Aggregated data by census tract provide spatial information with total counts of classes, such as age, gender, and head of household's personal income.

In addition, accessibility analysis requires data on a range of factors, particularly land use and transport systems. Land use data was obtained from Access to Opportunities Project (Pereira *et al.*, 2019) and have information about the distribution of formal jobs by educational level, i.e., low, medium, and high, aggregated by regular Uber H3 hexagons with 375-meter (diagonal).

The operational information of the transport system is also required. The bus system General Transit Feed Specification (GTFS) was provided by the Fortaleza Urban Transport Company (ETUFOR), an entity responsible for both public bus and taxi systems. The rail system GTFS was obtained from the Ceará Metropolitan Transport Company (METROFOR), which is responsible for the state's metropolitan rail system. In addition, bus and taxi fares were provided by ETUFOR, whereas rail fares were provided by METROFOR. All fare references are for August 2023 (see Table 1).

As ETUFOR does not have consolidated data on taxi service points, we obtained them from various sources, including: i) a taxi driver cooperative in Fortaleza (COOPRATRAF) that has taxi points geographically located, ii) OpenStreetMap (OSM), and iii) manual identification through the Google Street View platform. The data obtained from sources *i* and *ii* were cross-verified using Google Street View.

3.5.3 Spatial microsimulation

To address the challenge posed by the scarcity of individual data for CA applications, researchers have employed distinct approaches such as surveys (Cao; Hickman, 2019; Cooke *et al.*, 2022) and census microdata (Nahmias-Biran; Shiftan, 2020). While assessing a large city, such as Fortaleza, using the former approach is feasible only for government initiatives, the latter lacks the spatial resolution required for accessibility analyses.

In the realm of economics and public policy, spatial microsimulation has emerged as an effective technique for circumventing the scarcity of individual data with spatial attributes (Ballas *et al.*, 2013). Spatial microsimulation is a method for generating individual-level datasets, starting from the combination of individual microdata and geographically aggregated data, offering the benefits of producing diverse, high-quality outcomes and enabling the examination of policy distribution impacts at the individual level (Ballas *et al.*, 2013; Lovelace; Dumont, 2016).

This research uses Iterative Proportional Fitting (IPF), a spatial microsimulation method that finds common application in income-related studies, as is the case in the present study (Anderson, 2013; Panori, Ballas; Psycharis, 2017; Roszka, 2019). While IPF has been previously employed in transportation and accessibility investigations (Bittencourt; Giannotti, 2021; Bittencourt, Giannotti; Marques, 2021), different from prior research in this domain, we applied IPF results' as direct inputs to calculate individual accessibility-as-capability, considering factors such as income and other attributes.

The method generates a synthetic population that is consistent with a sample of individual data while matching count-based constraints from aggregated zone-level data. IPF results on the "most likely configuration" of individuals in the zones considering the constraint variables (Lovelace; Dumont, 2016). In simple terms, the IPF assigns weights to the individuals in the sample until a certain level of equivalence with the constraint variables is reached. With the weights assigned, individuals are replicated at the corresponding geographical levels (Lovelace; Dumont, 2016).

Some aspects are important to mention about the IPF technique. The method is easy to operationalise, with no evidence that more complex approaches result in greater accuracy in microsimulation results (Ramadan; Sisiopiku, 2020). In addition, the data needed are commonly provided by censuses around the world (Anderson, 2013; Lovelace; Dumont, 2016), consisting of individual sample microdata and categorial aggregated data at the census tract level, which work as constraint variables. This enables the proposed method to be widely used,

enabling its application even in cities with fewer available resources, aligning with the publicity and operationalisation criteria needed for justice assessment.

3.5.3.1 Model specification

The IPF model incorporates two key elements: the target variable and constraint variables (Lovelace; Dumont, 2016). The target variable represents the main specific individual attribute that we aim to estimate available on the microdata sample. In our case, we selected the household per capita income of the heads of household individuals, which is a main determinant of affordability.

The constraints variables (on aggregated data) should be related to the target variable (on the microdata) to enhance the estimation accuracy (Lovelace; Dumont, 2016). For income-focused modelling, such as this study, common constraint variables include age and gender (Panori, Ballas; Psycharis, 2017)

For constraint variables, we employed cross-tabulated categories as they retained more information within the microsimulation model (Lovelace; Dumont, 2016). These encompass different counts of specific characteristics from the census tract data, such as the number of men and the number of individuals with income less than one minimum wage. The constraint variables considered were i) cross-tabulated age and gender categories, with eight categories, four for each gender (e.g. the number of men aged 20 to 40 in each census tract); ii) cross-tabulated household position and personal income classes, with 11 categories (ten for head of household personal income and one single category identifying dependents, e.g. number of heads of household with personal income between one and two minimum wages); and iii) race, with three categories, such as the number of black individuals. For all constraint variables, 22 categories were considered.

After micro-simulating, it is expected to find a synthetic population of individuals whose attributes are consistent to those found in the sample of census microdata and align to the constraint variables associated to data from the census tracts. To adjust individual income for inflation, considering the census reference date of July 2010, we acquired inflation data from the Brazilian Central Bank for the period up to August 2023.

Finally, we linked the generated individual simulated data from census tracts to the hexagonal grid adopted in this research. To achieve this, we employed demographic data (population by gender) from the statistical grid to distribute the individual data from census tracts to hexagonal levels using areal-weighted interpolation. Then, the statistical grid data were firstly allocated to hexagonal level. Next, the simulated data were distributed using spatial

intersection to hexagonal level proportionally to demographic data by gender. For example, if a census tract intersects 50% of a hexagon in area, then the number corresponding to 50% of both men and women within that hexagon will be attributed to that census tract.

3.5.3.2 Model evaluation

The model evaluation was performed in two steps, as proposed by Lovelace and Dumont (2016): i) analysing the fit of the model's results to the aggregated data and ii) validating the model by comparing the modelled income with the observed average income of heads of household individuals at the census tract level.

The first step can be understood as an adherence analysis, which ensures that the simulated data indeed meets the constraints (Lovelace; Dumont, 2016). This step compares the total counts of individuals in the microsimulation results in each of the 22 constraint categories, with the actual values in each census tract used as constraint variables. We used three common literature indicators in this step (Lovelace; Dumont, 2016): i) Pearson's correlation between observed and modelled counts; ii) total absolute error (TAE), which indicates the absolute difference between the modelled and observed total counts across all categories. TAE calculates the difference for each category and the aggregate number provided by the microsimulation. The sum of each of these differences in a census tract is the TAE value; and iii) relative error is the TAE divided by the total population in each census tract.

Regarding the validation, we used the average personal income of the head of household provided by census in each tract as a validation variable. Although the target variable was the per capita household income of the household heads, the average data for this variable (i.e., the average household per capita income by census tract) was unavailable from the census. However, we found a high correlation (0.86) between the personal income and the per capita income of the household heads in the microdata sample. Therefore, we assumed that validating using the average personal income would ensure accurate estimation of the per capita household income for these individuals. Then, we employed a one-sample t-test to validate the microsimulation model for each census tract by comparing the modelled personal income of the household heads to their average income recorded in the aggregated census tract data.

Furthermore, it is important to note that personal income classes used as constraints in the microsimulation model are categorical variables with large ranges, with classes accounting for people between five and ten times the minimum wage. On the other hand, personal income is a continuous numerical variable. If the constraint variables are not well-chosen, just the personal income classes may not provide a good prediction of personal income

in the microsimulation. Therefore, this validation step is crucial for assessing the model specifications.

3.5.4 Distribution, inequality, and poverty analysis

We started the analysis about heads of households accessibility by a data overview, regarding descriptive statistics of income, affordability, and educational aspects across income deciles. In this context, affordability accounted for the proportion of individuals' income to afford the cost of 22 round trips, taking the bus system's fare as reference, which amounts to R$198 or $39.83. It represents the proportion of income required to afford daily engagement in job-related activities in a month. The bus system was chosen as a reference because it has a greater network coverage than rail services and has lower prices than taxi services.

Furthermore, it is also important to evaluate the role of individual heterogeneities in accessibility distribution. To this end, accessibility analysis focused on three aspects: i) spatial distribution analysis and descriptive statistics, ii) inequality assessment, and iii) poverty assessment.

The spatial distribution analysis focused on observing the overall variability of accessibility averages, given the nine scenarios considered relative to variations in time and budget thresholds (Table 2). This allowed us to explore behaviour of the proposed accessibility-as-capability measure and these spatial patterns.

The descriptive statistics analysis focused on the variability within each hexagon, going beyond measures of central tendency, and observing standard deviation, coefficient of variation, and skewness. This is needed to understand how aggregated accessibility measures can homogenise individuals' accessibility within spatial units and, consequently, impact justice assessment.

In inequality assessment we applied the Palma ratio, a prevalent metric for accessibility assessment (Guzman; Oviedo, 2018; Herszenhut *et al.*, 2022) that quantifies the ratio between the average accessibility of the wealthiest 10% (in monetary terms) and the average accessibility of the poorest 40% (Equation 11). A value closer to one indicates a more equitable distribution of accessibility. Notably, previous literature has categorised individuals based on the average income of spatial units rather than individual income (Guzman; Oviedo, 2018; Herszenhut *et al.*, 2022). By contrast, our method advances by directly considering individual income and classifying individuals based on their own earnings rather than spatial averages.

$$P = \frac{\bar{A}_{top,10\%}}{\bar{A}_{bottom,40\%}} \quad (11)$$

Regarding sufficientarian assessment, an important concept is chronic poverty. Chronic poverty reflects a condition of deprivation that hinders individuals' ability to raise living standards in long terms, leading to inescapable cycles of poverty - real "poverty traps" (Alkire et al., 2017). Bolch et al. (2023) introduced an approach aimed at addressing chronic poverty by simultaneously considering monetary and non-monetary deprivation at a specific point in time. Within the authors' method, the chronically poor are identified as individuals who fall below the income poverty line while also experiencing other multidimensional deprivations. This method has found practical applications in poverty assessments conducted by the World Bank (World Bank, 2022).

We propose adapting this concept for accounting accessibility and understanding individuals with accessibility-as-capability levels less than a given accessibility poverty line as the non-monetary poor. In the context of accessibility analysis, the definition of adequate accessibility is often ad hoc, with accessibility poverty lines indicating a minimum threshold for opportunities and lacking a consistent criterion (Hananel; Berechman, 2016; Miller, 2018; Pereira, Schwanen; Banister, 2017). Consequently, we explore a range of accessibility poverty thresholds, ranging from 1% to 50% of the total job opportunities available within the city.

So, the present work classifies as chronic poor individuals that, simultaneously: i) have per capita income below the World Bank's extreme poverty line of $2.15 USD per capita per day, or $64.5 USD by month; and ii) have accessibility-as-capability level below the accessibility poverty line. This was evaluated in all poverty line scenarios and showed through chronic poverty rates, which reflects the percentage of (monetary) poor individuals classified as chronically poor.

Chronic poverty may identify some of the most disadvantaged individuals within an urban landscape. This group holds particular significance for transport policy considerations because of its dual vulnerability to both transport-related and monetary social exclusion, especially in the context of fare policies and the financial burdens they entail.

To understand the impact of individual-level considerations regarding resources and conversion factors on accessibility-as-capability, we compare the proposed measure application (Section 3.5.1) with simpler estimates. This allowed us to assess how each consideration, specifically budget constraints and educational prerequisites, influenced inequality and poverty

analysis, measured using the Palma ratio and chronic poverty rates. To this end, we compared the following schemes for individual accessibility estimates with our complete accessibility-as-capability model:

a) Scheme 1 (S.1)–The conventional COM measure by transit, without restrictions on educational prerequisites and monetary budgets. It is the general reference since it is one of the most common measures in the accessibility literature. By comparing it with the complete application of the proposed measure, we can see the combined effect of individuals' constraints on accessibility, that is, monetary and educational constraints.
b) Scheme 2 (S.2)–The COM measure accounting for educational prerequisites by transit. In this measure, individuals have access to job opportunities within their educational level that are available from their location by transit. This measure is not restricted by individuals' monetary budgets. By comparing it with the complete proposed measure application, it is possible to observe the impact of individuals' monetary budgets.
c) Scheme 3 (S.3)–The proposed measure (Equation 4) calculated considering the average income by hexagon, instead of individuals' income, accounting for educational prerequisites, considering the mid-term budget threshold (15%). This scheme does not account for variations in the fares (see Table 1). By comparing it with the complete proposed measure application, it is possible to see the impact of variability in individuals' monetary budgets within hexagons.
d) Scheme 4 (S.4)–The proposed measure (Equation 4) calculated considering the average income by hexagon, instead of individuals' income, without accounting for educational prerequisites, considering the mid-term budget threshold (15%). This scheme does not account for variations in the fares (see Table 1). By comparing it with Scheme 5, it is possible to see the impact of accounting for educational constraints.
e) Scheme 5 (S.5): The COM measure by taxi, without restrictions on educational prerequisites and monetary budgets. This scheme represents a scenario without restrictions.

It is important to note that not all of these schemes are discussed in every aspect of the evaluation. The focus is on the schemes relevant to each discussion. In addition, some analyses focused on the mid-term scenario, with 30 minutes-threshold and considering 15% of

the monetary threshold (Scenario 6, Table 2), adopted as a point of reference for illustrative purposes.

3.6 Results

3.6.1 Spatial microsimulation

The microsimulation resulted in a synthetic population of more than 700 thousand head of household individuals. Table 3 presents the results of adherence evaluations. Across all parameters, the model exhibited high internal adherence, with a maximum relative error of 0.03%, which was very close to zero. This outcome suggests that the simulation performed well with a good selection of constraint variables considering the sample microdata, resulting in a good fit.

Table 3 - Adherence analysis

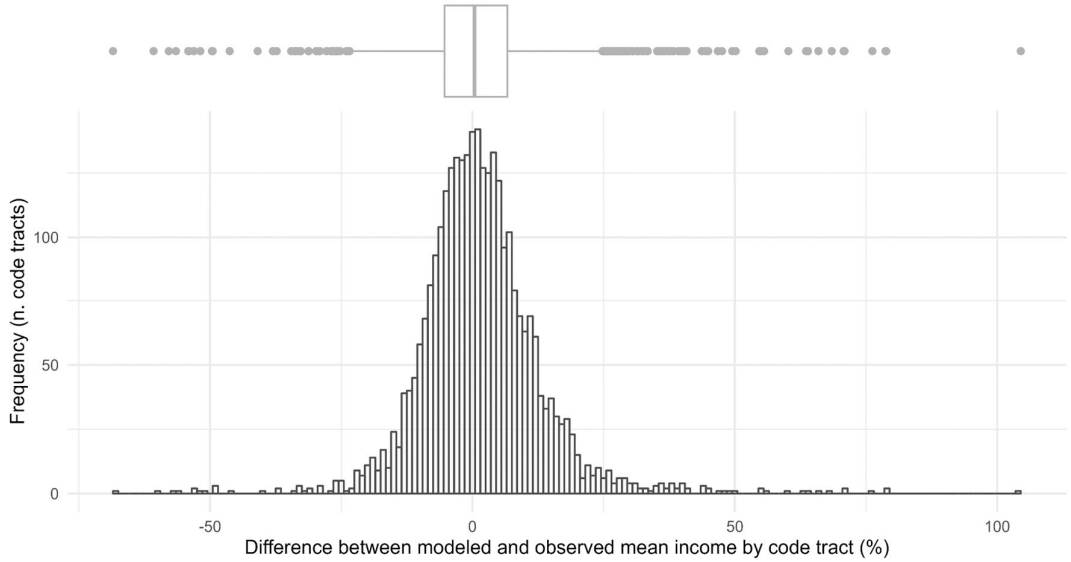
Parameter	Values		
	Minimum	**Median**	**Maximum**
Pearson's correlation between observed and modeled counts	~1.00	~1.00	~1.00
Total absolute error (TAE) among census tracts	0	0	40
Relative error (RE) among census tracts	0	0	0.03%

Source: Author's own elaboration.

Figure 4 presents the disparity between average personal income in the microsimulated data and the census average income of heads of households. Notably, the absolute overall median difference amounts to 5.83%, equivalent to R$48.6 or approximately $9.80 USD, across the census tracts.

Regarding the model validation, the one-sample t-test conducted across all census tracts yielded compelling results. In 89.29% of the census tracts, the statistical analysis did not provide evidence to refute the null hypothesis (H0), suggesting that the average income of the microsimulated data aligns with the census-observed average income within a 95% confidence level (this increases to 95.34% of the census tracts within a 99% confidence interval). For the remaining 10.71% of the census tracts, for which H0 was rejected, the data revealed a median absolute difference of 17.10%.

Figure 4 - Histogram of the difference between microsimulated and census average personal income of head of household individuals by census tract.



Source: Author's own elaboration.

After microsimulation, we conducted the data treatment, removing from analysis individuals aged below 18 or over 65, as well as those lacking educational or other information, remained in the dataset at around 593 thousand individuals. Notably, this data refinement resulted in the removal of more than 100 thousand individuals, of which more than 87,000 individuals were aged above 65 years. It is worth mentioning that a significant proportion of the older people (over 80 %) did not participate in any paid activity.

All analyses, percentages, and other references in the following section will be regarding these 593 thousand head-of-household individuals.

3.6.2 Accessibility analysis

3.6.2.1 Data overview

Table 4 provides a summary of individual data, highlighting income, affordability, and educational aspects. The table shows how low-income individuals, that is, in the first and second income deciles, are deprived of access to bus system services, whereas wealthier individuals need to allocate less than 6% of their income to cover all their job-related round trips.

Furthermore, only 3.3% of the heads of households in the first decile have a high educational level, while this parameter in the tenth income decile is over 18 times higher. High-

income individuals not only have more affordability for transportation but also enjoy a wider range of job opportunities thanks to their higher educational levels.

Table 4 - Heads of households' individual data overview: income, affordability, and educational level.

Decile	Per capita income (USD*)		Monthly Affordability (%) Bus system		Educational level		
	min	max	min	max	Low	Middle	High
1	0.00	44.21	**90.12**	-	78.47%	18.22%	**3.31%**
2	44.21	73.32	54.34	90.12	79.55%	19.93%	0.52%
3	73.32	104.95	37.96	54.34	77.15%	22.02%	0.83%
4	104.95	129.39	30.79	37.96	72.25%	26.27%	1.48%
5	129.39	164.97	24.15	30.79	65.94%	31.82%	2.24%
6	164.97	217.08	18.35	24.15	55.86%	39.62%	4.51%
7	217.08	259.64	15.34	18.35	56.15%	39.08%	4.77%
8	259.64	388.17	10.26	15.34	39.03%	48.63%	12.34%
9	388.17	733.06	5.43	10.26	25.01%	45.81%	29.18%
10	733.06	86309.16	0.05	**5.43**	9.68%	29.00%	**61.32%**

Source: Author's own elaboration.
*Values converted using the dollar exchange rate of R$4.97 as of the end of September 2023.

Another important element is the distribution of job opportunities across education levels. Low educational level job activities represent 22.65% of total opportunities in the city, while mid-level represents 63.79%, and high level 13.56%. Consequently, individuals with low formal education have access at most to 22.65% of total opportunities, while mid-level individuals have access to 86.44% of opportunities, and higher-level individuals have access to 100%.

Table 5 summarises the relationship between the availability of job opportunities and educational level for each per capita income decil. This table shows the proportion of job opportunities available to individuals, based solely on educational prerequisites. It is evident that significant disparities exist between individuals due to their educational level, even before considering the impact of transportation and spatial factors. This also shows that these disparities are highly correlated with income.

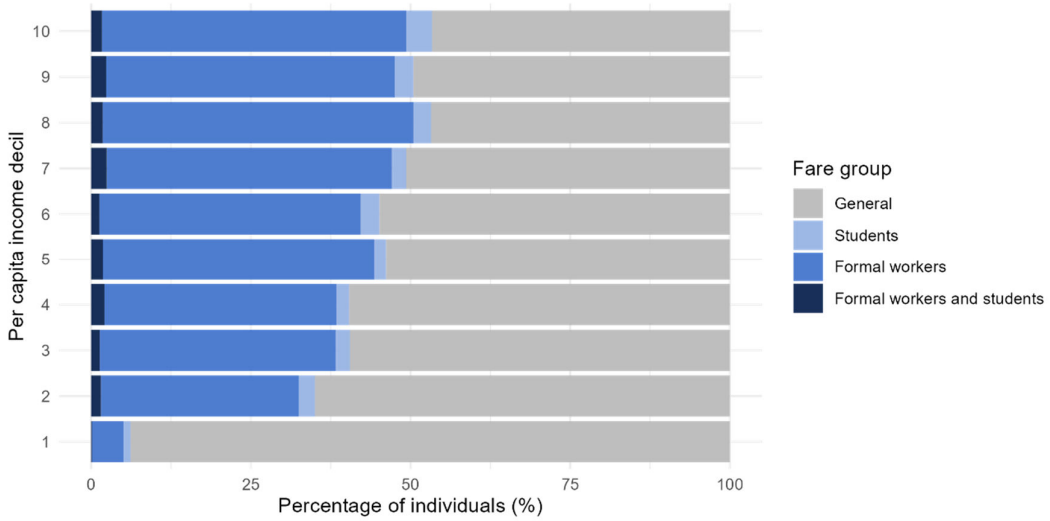
Table 5 - Average available opportunities considering educational prerequisites in formal jobs, by decil.

Decil	Average available opportunities (% of total job opportunities)
1	36.84
2	35.76
3	37.34
4	40.55
5	44.69
6	51.42
7	51.27
8	63.22
9	74.44
10	88.58

Source: Author's own elaboration.

Figure 5 provides an overview of the distribution of individuals across various fare groups (see Table 1). As highlighted in blue tones, the higher the income, the higher is the number of individuals benefiting from a fare discount or subsidy. This observation reveals a situation where higher-income individuals not only pay less for transportation in proportional terms but also in absolute terms. This implies that the primary focus of these policies may not be to enhance accessibility for the poorest, which maybe should be the objective of any fare policy, and raises issues regarding their implications through the lens of justice.

Figure 5 - Distribution of individuals by fare group, by decil.



Source: Author's own elaboration.

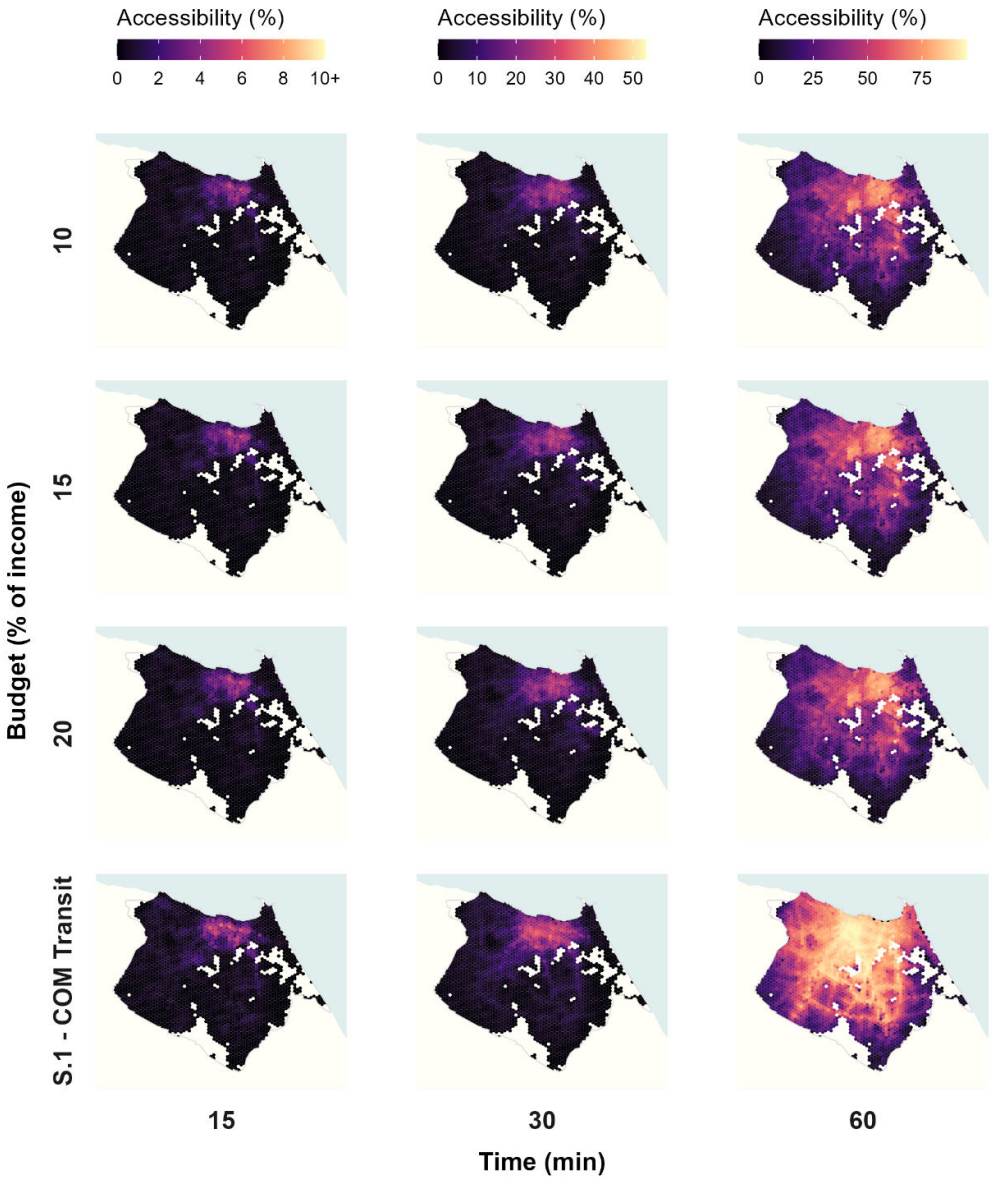
3.6.2.2 Descriptive statistics and variability analysis

Figure 6 presents the spatial pattern of accessibility for each scenario, calculated using the proposed measure, as the average accessibility among individuals within each H3 hexagon. The overall spatial patterns of accessibility have similarities to those obtained using the conventional COM measure by transit without educational prerequisites (Scheme 1) across different travel time thresholds.

However, it is crucial to emphasise that accessibility values exhibit significant differences. This is particularly evident in the spatial distribution at the 60-minute threshold, where proposed measure showed slightly lower accessibility levels around transit corridors (Figure 6). The network contours are less apparent in the proposed measure estimates than in the COM measurement results, evidencing the variability of accessibility when accounting for constraints. This also indicates that the presence of transport networks alone does not imply greater accessibility owing to individuals' constraints.

At the 60-minute threshold, COM measures clearly overestimated accessibility, indicating a median access to 56.4% of all opportunities, whereas our proposed measure, with a budget threshold of 20%, showed a median access of only 23.1%. This overestimation becomes even more apparent when we consider that for 47% of the Economically Active Population (EAP) in Fortaleza, which has a low educational level, the maximum accessibility is below 23% of available job opportunities.

Figure 6 - Spatial pattern of accessibility given by average values in each H3 Hexagon, by time and budget scenarios, in addition to Scheme 1 (COM measure by transit).

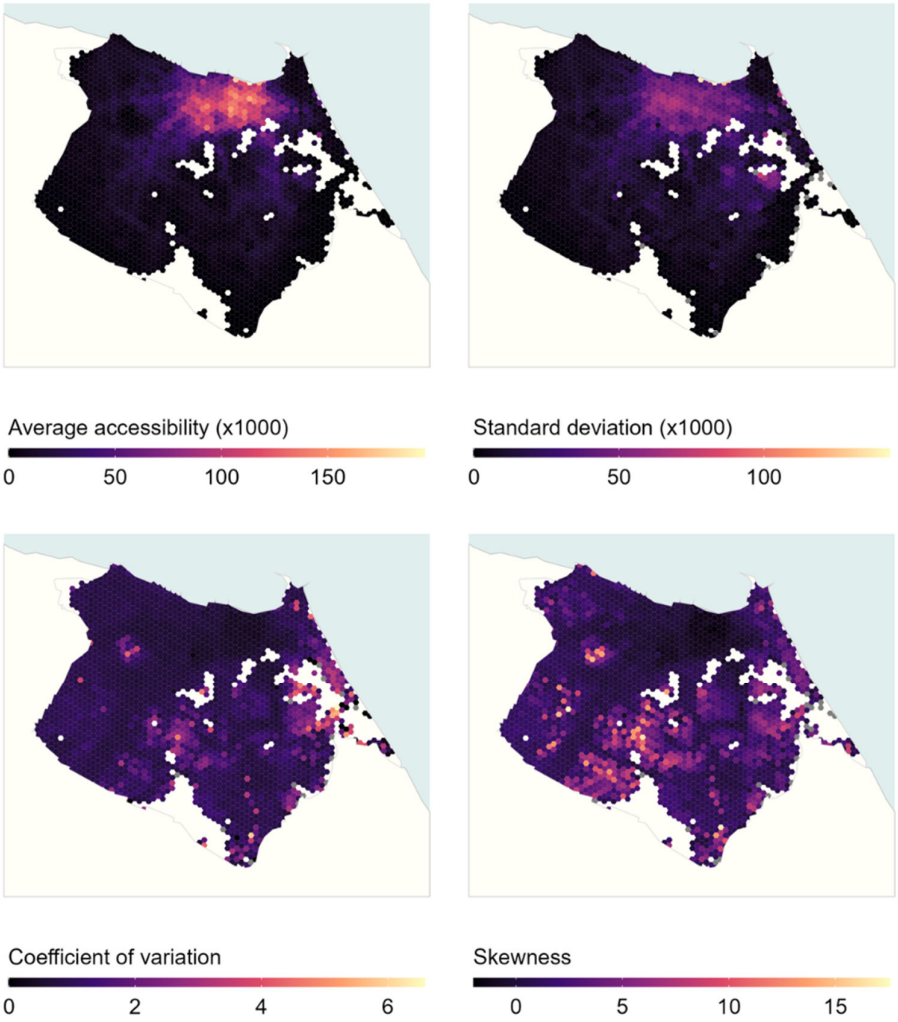


Source: Author's own elaboration.

Although average spatial patterns provide information about public transport provision and activity location, they may not provide real information about individuals' accessibility. Taking the mid-term scenario of a 30-minute threshold and a 15% budget constraint as an example, Figure 7 shows the spatial distribution of the proposed measure that estimates the variability within each H3 hexagon. As illustrated, there is a substantial coefficient

of variation and skewness in some peripheral areas where the overall average accessibility is comparatively lower.

Figure 7 - Descriptive statistics of proposed measure estimate. Scenario of 30-minutes threshold and 15% of budget.



Source: Author's own elaboration.

The high variability shown by the coefficient of variation in these areas reveals that by not considering individual heterogeneities in the measure, accessibility could be biased, especially for the poor, which are the major populations within these areas. In addition, the high positive skewness indicates that this bias corresponds to overestimation of accessibility, as most of the individuals had accessibility levels concentrated below the average. This shows compelling arguments about how the application of aggregated scenarios on accessibility

estimates, such as the use of average income, may mask substantial disparities among individuals.

3.6.2.3 Inequality

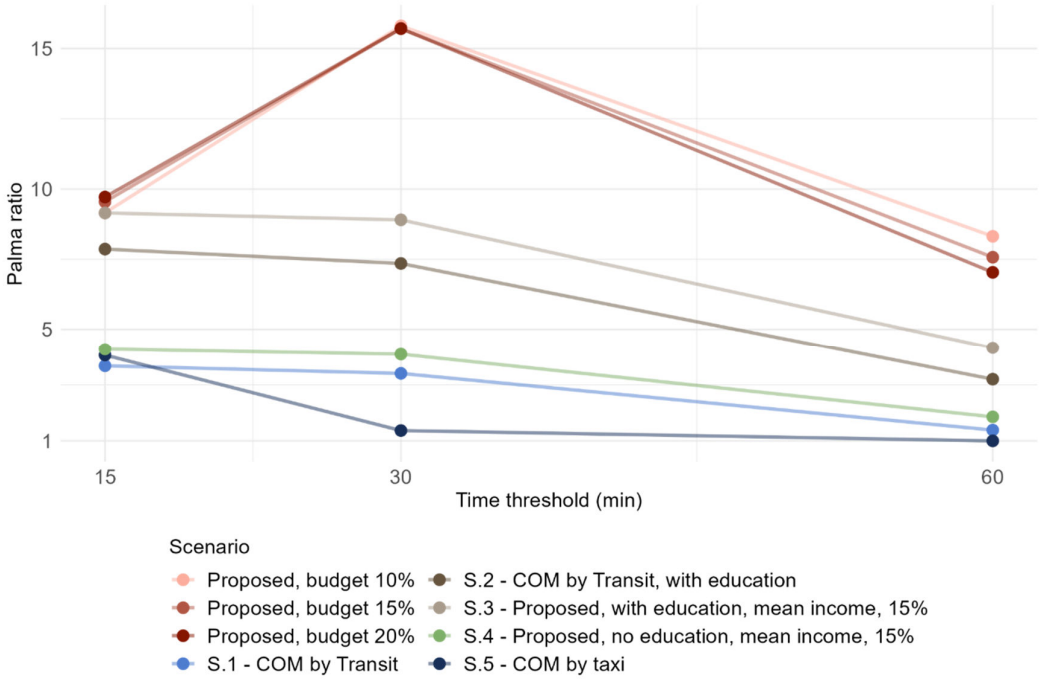
Palma ratio results across the proposed measure scenarios (Table 2) and measuring schemes (see Section 3.5.4) are shown in Figure 8. As we can see, across all scenarios, the proposed measure reveals a major inequality. For instance, the proposed measure results indicate that in the 30-minutes scenario, high-income individuals have, on average, more than 15 times the accessibility of low-income individuals. In the 60-minute scenario, this inequality diminishes to approximately 7.5 times.

Measuring the Palma ratio using the accessibility results of Scheme 1 (relative to the traditional COM measure by transit) consistently yielded inequality levels of less than half of our proposed measure. To illustrate, in the 30-minute threshold scenario cited previously, the accessibility estimated by the proposed measure exhibited an inequality more than four times higher than that estimated by the COM measure.

This disparity in outcomes underscores the cumulative impact of accounting for various factors within our proposed measure, related to heterogeneity aspects (or sources of inequality), such as individuals' monetary budgets (which also influence access to the taxi mode for wealthier individuals), fare policy scenarios, such as the student fare policy (Table 1), and educational prerequisites. These results serve as compelling arguments that emphasise the critical importance of considering individual heterogeneities in accessibility assessments. Failure to account for these factors might lead to misleading information about accessibility inequality.

The disparities in the Palma ratio estimates between Scheme 2 (COM measure by transit, accounting for education prerequisites) and our proposed measure scenarios, as shown in Figure 8, highlight the substantial influence of both individuals' income and variations in fares (as outlined in Table 1). Notably, the proposed measure exhibits an inequality up to 160% greater than that of Scheme 2. This emphasize how disregarding the monetary role may significantly underestimate inequality. This also highlights the need to conduct more in-depth research to assess the monetary role from a capabilitarian perspective. It is especially important to advance accessibility perspectives for fare policy planning and evaluation.

Figure 8 - Palma ratio across proposed measurement scenarios and schemes according to time, monetary budget, and education constraints.



Source: Author's own elaboration.

Scheme 3, calculated using the proposed measure (Equation 4) with the hexagon's average income (see 3.5.4), resulted in Palma ratio estimates that were very different from the proposed measure scenarios. The proposed measure scenarios display Palma ratio estimates up to 92% greater than those in Scheme 3, underlining the influence of affordability heterogeneities on accessibility inequality. In this context, affordability refers to the compound effect of fare policy scenarios and income variation across individuals.

Previous studies evidenced the impact on inequality of accounting for monetary costs in accessibility by zonal aggregated perspective (Herszenhut *et al.*, 2022). Our results go further, evidencing this monetary effect vis-à-vis individuals' income and fare specificities, underscoring the importance of consider individuals' income variability to assess accessibility.

The differences between Schemes 3 and 4 (same as Scheme 3, without considering education prerequisites) reveal the magnitude of the role played by educational constraints on accessibility inequality. By adding educational constraints to the proposed measure, the Palma ratio measures increased up to 133%. This is a compelling argument against methods that

disregard educational constraints when evaluating job accessibility. Evaluations that disregard resources and conversion factors, such as COM measures, or which widely aggregate them, such as measures relying on mean income, are likely to underestimate inequality, particularly in the context of longer time thresholds.

Moreover, with accessibility measures that account for individual heterogeneities, we can see group differences that are not possible in the aggregated analysis. For instance, in all scenarios, it was observed that male heads of household individuals have, on average, greater accessibility than female heads, all holding statistical significance within a 95% confidence interval. In the scenario with a 60-minute threshold and 10% budget, a noteworthy difference of 19.9% in average accessibility between male and female heads of households in the city becomes apparent. This could be a result of a compound effect of income and educational level. Although this study does not delve into the detailed profiles of these inequalities, it underscores the need for further in-depth research to better comprehend and address these disparities, which fall beyond the scope of the current work.

3.6.2.4 Poverty

Poverty analysis focuses on individuals whose income fell below the extreme poverty line of $64.5 by month. This group comprises approximately 94 thousand individuals, constituting 15.5% of the heads of household individuals considered in the analysis. These individuals have a median income of $32.4 and pertain to the first and second income deciles.

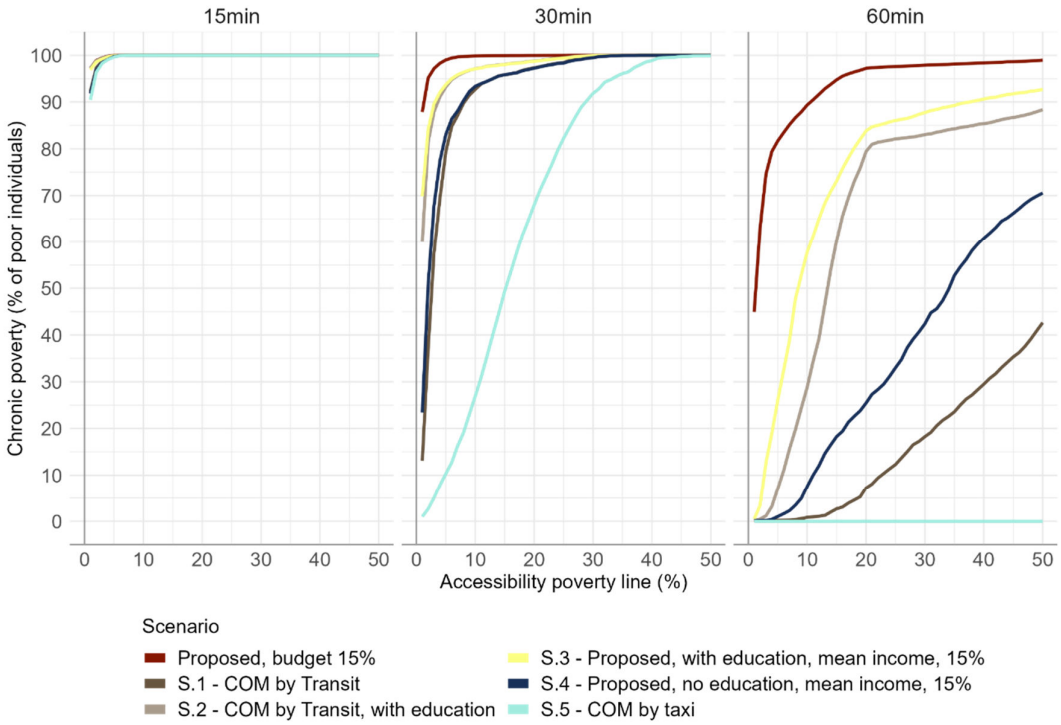
The results for the chronic poverty index are shown in Figure 9. Notably, there are minimal differences in estimates between scenarios with 15 and 30-minute thresholds, all identifying almost 100% of poor individuals as in deprivation of accessibility, except for the case where access to all modes, including taxis, is not restricted (Scheme 5). This observation underscores the significant impact of individual motorised modes on overall accessibility inequality.

The low variability in the 15- and 30-minutes analysis is related to job spatial distribution and public transport supply in the city, which does not provide the possibility of poor access activities within less than 30 minutes. Therefore, we will focus on the results to 60-minutes threshold.

As shown in Figure 9, the proposed accessibility measure reveals a greater number of extremely poor individuals living deprived of accessibility when compared with all other measures across all accessibility poverty line values. For instance, in comparison with Scheme

1, the proposed measure pointed out up to 92.5% more people living in chronic poverty, within the 60-minutes threshold scenario.

Figure 9 - Percentage of chronic poverty among heads of household by scenario.



Source: Author's own elaboration.

Our proposed measure shows that in the 60-minute threshold scenario, 45% of the extremely poor individuals could not access even 1% of the total opportunities in the city. Considering that almost 80% of them had a low educational level (Table 4), and 31.6% had no income, this is not surprising. These individuals have just access to low-education level jobs and, due to income, have no access to public transport. The other measures, however, do not account for this, underestimating the chronic poverty faced by many individuals in the city.

Another critical aspect to consider regarding extremely poor individuals is that nearly 60% were not engaged in any paid activity in the reference week of the census. Only 8% of them were students. In summary, these individuals lack income, do not have formal jobs, and have no access to education. Consequently, they cannot afford transportation because of their lack of income, they do not benefit from subsidised passes in public transportation due to their non-employment status, and they do not receive any pass discounts due to their lack of educational access. These individuals are really facing a "poverty trap" and our proposed measure could capture this, not mask this multidimensional deprived condition.

We can draw several comparisons between the scenarios, as discussed in Section 3.6.2.3. However, it is important to emphasise the comparison between the COM measure by transit and accounting for educational prerequisites (Scheme 2). The proposed measure shows an index of chronic poverty that is up to 76.25% higher than that in Scheme 2. Since we control for education, this difference concerns the impact of affordability issues on accessibility, related to the association between the monetary constraints of individuals and the fare policy scenarios faced by them.

This difference could also be interpreted as the potential impact of fare policies on lifting individuals from the chronic poverty group. As an example, if we consider a poverty line of 20% of opportunities in a 60-minutes threshold accessibility, a fare-free transit policy could lift 17.8% of monetary poor from chronic poverty scenario.

Measures that account for individuals' income and fare scenarios more broadly, as proposed by the present work, have the potential to inform the development of more effective fare policies aimed at addressing chronic poverty associated with accessibility. This topic also presents an avenue for further investigation in the realm of transport justice.

3.7 Discussion and conclusions

This study introduces an innovative method for measuring accessibility from a capability approach perspective. Which opportunities are really available to an individual? What can they access? The proposed method provides a person-centred accessibility measure to better understand these issues, as well as a way to operationalise this. We can highlight some key advancements: i) provide an objective measure of accessibility-as-capability in individual-level; ii) incorporate individuals' heterogeneities on access, such as the related with monetary budget constraints as well as conversion factors, such as fare policies scenarios and education; iii) the proposed measure is particularly sensitive to disparities in the monetary budget, accounting for the number of trips that individuals can afford; iv) could incorporate multiple modes, restricting mode access by individuals monetary budget; and v) opens the door to large-scale applications by leveraging common available public data.

Furthermore, this study investigated the role of individual heterogeneities in accessibility inequality and poverty through a case study conducted in Fortaleza (Brazil). This application focused on job accessibility and incorporated individuals' monetary aspects related to income disparities and fare policy variations (i.e., discounts and subsidies) as well as educational prerequisites for job activities.

The findings showed that individual heterogeneities play a pivotal role in accessibility. Both monetary and educational constraints have a substantial and systematic impact on accessibility inequality and poverty, underscoring that disregarding these elements and their variability may result in significantly misleading information about the real condition of accessibility inequality and deprivation faced by individuals.

Furthermore, transport policy planning could benefit from considering the proposed method, especially because of its potential coverage in population terms and its significant sensitivity to individuals' realities. Notably, the results draw attention to the valuable role that our measure can play in shaping fare policy decisions. For instance, it can quantify the potential of a fare-free transit policy, a growing policy in cities around the world. How much does this policy help to mitigate chronic poverty on accessibility, that is, by removing monetary-poor individuals from accessibility poverty? And about equity? Since our analysis is exploratory, fare policy issues require careful attention in further studies from both inequality and poverty perspectives.

There are several imperative factors not accounted for in the present work that influence job accessibility. In CA, feminist perspectives highlight how gender roles affect women's employment capabilities relating to childcare responsibilities (Robeyns, 2008b, p. 91). In addition, Robeyns (2017b, p. 97-98) argues that the employment capability of women maybe be less "robust" than of a man, since the former has less effective probability of been succeed professionally, "given a variety of mechanisms that are biased against female professionals". From the results of this application (3.6.2.3), we could see an initial glimpse of the deeper complexities of gender inequalities, showing only a general disparity. However, it is imperative that further studies go deeply in this issue, which could benefit from the capability perspective proposed in this work.

It's essential to acknowledge certain limitations within this application. Our study applied uniform monetary thresholds to per capita income as a proxy for individuals' disposable income. This approach may underestimate inequality, as it does not account for the potential of richer individuals to expend relatively more in transport without having deleterious effects on other parts of their lives. Further research could explore alternative methodologies, such as modelling individual expenditures based on household budget surveys or implementing microsimulations with cross-database sources.

Furthermore, we did not evaluate potential variations resulting from differences in spatial microsimulation specifications, and other spatial treatments, concerning individual accessibility. Future research could explore these variabilities on accessibility estimates by

running microsimulations with different specifications (e.g., with different constraints). This could produce a type of “confidence interval” to the estimates of equality and poverty, as well as in the context of accessibility-as-capability measurements.

This study also does not consider some important transportation systems, such as bike-sharing systems, ride-hailing services, or even individual modes (e.g., cars, bicycles, motorbikes). To represent part of the accessibility provided by individual motorised modes, we considered the taxi mode in a simplified manner because we do not directly have data about fares. In addition, our application focused on the specific factors of job accessibility. Further studies could explore the role of these transportation systems in inequality and poverty through the proposed method, accounting for other activity types. A noteworthy aspect to mention is that these studies could encompass another range of conversion factors and accessibility issues. For instance, bike-sharing studies could be focused on physical restrictions on access to bike-sharing systems and encompass the role of electric bikes on access of the people with physical disabilities.

4 CONCLUSIONS

The nexus between accessibility and inequality has been discussed in transportation research for several decades (Knox, 1980; Wachs; Kumagai, 1973). During this period, theoretical advancements on transport justice has underpinning the role of accessibility as a core measure to assess poverty and inequality on urban space, through the lens of diverse theories of justice (Lucas, Wee, van; Maat, 2016; Luz; Portugal, 2022; Martens, 2016, 2019; Martens; Golub, 2012; Pereira; Karner, 2021; Pereira, Schwanen; Banister, 2017).

Across these theories, capability approach has emerging as a promising framework to address justice concerns on accessibility (Azmoodeh, Haghighi; Motieyan, 2023; Cao; Hickman, 2019; Cooke *et al.*, 2022; Deka, 2022; Hananel; Berechman, 2016), especially due to its conceptual relation with people heterogeneities and opportunities. While some studies have concentrated on establishing a discourse between accessibility and CA concepts, positioning accessibility as a pivotal metric on this framework on transport context (Pereira, Schwanen; Banister, 2017; Vecchio; Martens, 2021), there remains a notable absence of research dedicated to elucidating directly on measurement domain the conceptualization of accessibility-as-capability. More specifically, there is a lack of studies addressing theoretically and in practical terms what measuring accessibility-as-capability means, outlining the requisites and implications to this type of measure.

To address that, this dissertation provided a theoretical and practical pathway to account for CA on accessibility measurement domain. In the theoretical realm, Chapter 02 introduced a framework for the development of accessibility-as-capability measures, providing the formal structure, core criteria, and operational suggestions to this development. This pathway also permeates the convergence between Rawls' theory of justice and CA on transport, by incorporating primary resources into accessibility-as-capability measures through monetary factors. This framework was put in practice in Chapter 03, through the development and implementation on a case study of a novel accessibility-as-capability measure that account for individuals' heterogeneities. The proposed framework focuses only on accessibility as a metric for transport justice, a small piece of a broader theory of justice for transport phenomena. Previous studies have made advancements in other parts of this theory, especially those related to distributive rules in accessibility (Martens, 2016; Pereira; Karner, 2021; Pereira, Schwanen; Banister, 2017). However, accessibility is a very complex concept, covering a wide range of capabilities (e.g. work, education, and leisure, each related to different accessibility as a capability), what was not in-depth discussed in relation to distributive rule on transport. What is a fair condition for the transport system considering all these capabilities? If people are

deprived in all accessibility domains (what is a common situation, especially in cities of global south), what should be treated first? This problem is related to the weighting issue, and solving the trade-off between these capabilities, in addition to other related capabilities in the urban context (e.g. housing), is a critical issue in building a complete transport justice theory.

Throughout this research, it has become evident the challenges to account for CA on accessibility, but also underscore its benefits. Contrasting with general accessibility measure, CA has a particular demand for objective and disaggregated perspectives. We underscored those individual heterogeneities, stemming from factors such as monetary budget constraints, and educational prerequisites play a pivotal role in shaping accessibility inequalities. The analysis conducted in Fortaleza showed the significant impact of these factors, providing a compelling contrast to measures that overlook these critical nuances.

Through the application of the proposed measure, we were capable to shed light on a substantial portion of heads of household trapped in chronic poverty, by monetary and accessibility aspects, facing conditions that probably could perpetuate their deprived situation. By enabling the detection of these realities, our measure offers a way to account for that on transport planning, helping policymakers to build policies that directly address that, specially fare policies.

Further studies could go deeper into chronic poverty evaluation. What is its relationship to effective participation in activities? Does chronic poverty have generational impact on accessibility? How does chronic poverty relate to social mobility? These questions are important for enforcing the accessibility agenda, demonstrating how its promotion is important for social justice.

It is important to note that the study case focused only on the heads of households, in aspects related to affordability and educational constraints. The overall pattern of inequalities in the city, considering all people, may be slightly different. In specific terms, future work could recalibrate the microsimulation and apply it to the entire city population. From a broader perspective, future work could encompass other factors of inequality and deprivation, such as age and gender.Another important point regarding advancing CA in accessibility measures is competition. As discussed, some capabilities are only accessible to individuals if others do not wish to pursue or attain the same capability (Robeyns, 2006), which is the case with accessibility. Previous studies have shown that job-accessibility measures that account for competition have a higher correlation with employment than non-competitive measures (Merlin; Hu, 2017). This finding indicates that competition has a real impact on people’s capabilities. Future research should develop accessibility as a capability measure that accounts

for competition, and investigate the interrelationships between competition and other conversion factors on accessibility inequalities and deprivation.

The application conducted in this dissertation also did not account for homeless populations since the Brazilian Census has no data about these people. There is a scarcity of studies that observe this population in transport field (Murphy, 2019). These people are subject to poverty, harassment, violence, and the environment more than all other city inhabitants. It is imperative that further studies on accessibility as a capability observe the conditions faced by these populations, since they are one of the most disadvantaged people in urban areas. How do transportation systems promote opportunities for them?

There are several conversion factors that remain unaddressed on capabilitarian applications on accessibility, opens an avenue for future research. For instance, the exploratory analysis conducted in Chapter 03 observed that male head of household have on average higher levels of accessibility than female ones. Addressing gender-related inequalities in depth necessitates further research focusing on their determinants within the accessibility context. These investigations can greatly benefit from the adoption of the proposed theoretical framework and measure of accessibility-as-capability.

The application on Chapter 03 has primarily focused on job accessibility, so future research could extend into assessing different activity types, thereby encompassing an even wider range of conversion factors and accessibility concerns. These investigations can also add transportation mode options not accounted for in this work, especially ride-hailing and active options. For instance, some of them could focus on the role of active transport modes on accessibility, e.g., bike-sharing systems, evaluating how physical conditions could deprive accessibility. In summary, the discussions within this dissertation proposed a pathway toward accessibility-as-capability measurement within transportation domain. Accounting for several factors that may generate inequalities and deprivation on accessibility constitutes a major challenge, revealing gaps for future research.

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