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UNDERSTANDING TRANSPORT-RELATED SOCIAL EXCLUSION THROUGH THE LENS OF CAPABILITIES APPROACH: DOES BETTER ACCESSIBILITY HELP TO REDUCE SOCIAL EXCLUSION?

Gregório Costa Luz de Souza Lima

Dissertação de Mestrado apresentada ao Programa de Pós-graduação em Engenharia de Transportes, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Mestre em Engenharia de Transportes.

Orientador: Licinio da Silva Portugal

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"There should be no obstacles to accessing knowledge."

Alexandra Elbakyan

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COMPREENDENDO A EXCLUSÃO SOCIAL RELACIONADA AOS TRANSPORTES ATRAVÉS DA LENTE DA ABORDAGEM DE CAPACIDADES: MELHOR ACESSIBILIDADE CONTRIBUI PARA REDUZIR A EXCLUSÃO SOCIAL?

Gregório Costa Luz de Souza Lima

Dezembro/2021

Orientador: Licinio da Silva Portugal

Programa: Engenharia de Transportes

A dissertação aborda o fenômeno da exclusão social relacionada ao transporte, explorando seus aspectos teóricos e práticos. A contribuição desta dissertação é tripla. A primeira contribuição é o estabelecimento de uma estrutura teórica ampla e detalhada baseada na Abordagem de Capacidades de Amartya Sen sobre como os indivíduos podem ser impedidos de viajar e acessar oportunidades que valorizam e como isto pode os levar à exclusão social. A segunda contribuição foi fornecer uma estrutura analítica para avaliar a aderência de medidas de acessibilidade para avaliar o fenômeno da exclusão social relacionada ao transporte. Além de considerar a consistência teórica das medidas de acessibilidade, a estrutura analítica também incorpora aspectos relacionados com a usabilidade e a interpretabilidade das medidas. Com base na estrutura analítica desenvolvida, foram avaliadas 24 medidas de acessibilidade. A terceira contribuição foi fornecer evidência causal da relação entre acessibilidade e participação em atividades. Um modelo de regressão Poisson associado a uma estratégia de identificação de variável instrumental foi utilizado para avaliar o efeito causal entre acessibilidade e participação em atividades totais, obrigatórias e discricionárias na cidade de São Paulo.

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UNDERSTANDING TRANSPORT-RELATED SOCIAL EXCLUSION THROUGH THE LENS OF CAPABILITIES APPROACH: DOES BETTER ACCESSIBILITY HELP TO REDUCE SOCIAL EXCLUSION?

Gregório Costa Luz de Souza Lima

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The dissertation approaches the transport-related social exclusion phenomenon, exploring its theoretical and practical aspects. The contribution of this dissertation is three-fold. The first contribution is the establishment of a broad and detailed theoretical framework based on Amartya Sen's Capabilities Approach about how individuals may be prevented from travelling and accessing valued opportunities and how this may lead to social exclusion. The second contribution was to provide an analytical framework for assessing the adherence of accessibility measures to assess the transport-related social exclusion phenomenon. Besides considering the theoretical consistency of the accessibility measures, the analytical framework also incorporates aspects related to the usability and interpretability of the measures. Based on the analytical framework developed, 24 four accessibility measures were assessed. The third contribution was to provide causal evidence of the relationship between accessibility and activity participation. A Poisson regression model associated with an instrumental variable identification strategy was used to assess the causal effect between accessibility and participation in total, mandatory and discretionary activities in the city of São Paulo.

Publications

The work presented in Chapters 2 to 4 has appeared or has been submitted to the following peer-reviewed journals:

1. Luz, G. & Portugal, L. (2021) Understanding transport-related social exclusion through the lens of capabilities approach, **Transport Reviews**, DOI: 10.1080/01441647.2021.2005183 (Chapter 2)

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3. Luz, G., Barboza, M. H. C., Portugal, L., Giannotti, M., van Wee, B. *(under review)* Transport-Related Social Exclusion: Does Better Accessibility Help to Reduce Social Exclusion? Evidence From the City of São Paulo. Submitted to *Transportation Research Part A: Policy and Practice*. (Chapter 4)

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Chapter 1

Introduction

1.1 Transport Planning and Social Exclusion

The ultimate goal of transport planning and the social inclusion notion are closely related. Initially, traditional transport planning was based on the "predict and provided" rationale and aimed to ensure effective and efficient movement of people and goods. Due to the criticism that the "predict and provide" approach has suffered and continues to suffer to this day, there has been a paradigm shift regarding the objectives to which transport planning should contribute. Over time, transport planning practice evolved from the classical "predict and provide" and later "predict and prevent" to the accessibility planning (Banister, 2008; Boisjoly and El-Geneidy, 2017a; Te Brömmelstroet and Bertolini, 2011).

The "predict and provide" rationale (Owens, 1995), i.e. forecasting future travel demand and providing the necessary road infrastructure to accommodate motorised traffic, although still dominant in many places, is subject to at least two criticisms. The first is that identifying solutions to end congestion across the entire transport network would be the outcome of transport planning in a world of unlimited resources (Martens, 2016b). Increasing financial and fiscal constraints make expanding urban transport systems increasingly difficult (Bertolini *et al.*, 2008). Because transport is a phenomenon of induced demand, the construction and widening of roads is only a short term congestion relief (Cervero, 2001). The second criticism is that by deriving future travel demand from existing travel patterns (Martens and Hurvitz, 2011), it assumes that traffic flow is a result of free choice and disregards that travel demand is also a result of constraints experienced by individuals (Martens, 2006, 2016b; Pereira *et al.*, 2017). Thus, the four-step model on which the "predict and provide" planning is based implicitly predicts strong trip growth among segments of the population with relatively few travel restrictions while forecasting little growth for groups with more significant travel impediments (Martens, 2016b). By ignoring the fact that current travel patterns reflect how transport resources have been distributed in the past, such transport planning models create a feedback loop and reinforce the mobility gap across the population (Martens, 2006, 2016b; Wachs and Kumagai, 1973).

Criticism of the "predict and provide" practice of traditional transport models and concerns about environmental sustainability led to the emergence of a new planning approach, the "predict and prevent" (Cervero, 2001; Marvin and Guy, 1999; Owens, 1995). The new approach shifted the focus from the technical approach that emphasised supply-side initiatives (meeting demand) to an orientation to travel demand management, focused on reducing reliance on road construction and travel need (Vigar, 2000). However, the "predict and prevent" approach is not without critics. The focus on reducing travel demand implicitly assumes improving environmental quality as an objective of the transport system (Bertolini *et al.*, 2008; Martens, 2016a). However, this goal neglects the fact that mobility is essential for active participation in the economic and social life of most societies (Bertolini *et al.*, 2008; Cass *et al.*, 2005; Urry, 2007). In this sense, some authors suggest that it is more appropriate to perceive the environmental issue as a constraint to transport planning rather than a goal in itself (Bertolini, 2017; Martens, 2016a; Owens, 1995).

Both the "predict and provide" planning approach, seen as a technical exercise to increase travel speeds and end congestion, and the "predict and prevent" approach, focused on reducing pollutants emissions, fail to specify the ultimate goal of transport planning (Martens, 2016b). As widely accepted, movement is rarely an end in itself, but usually, a means to another end (Bertolini *et al.*, 2008; Cervero, 2001; Denmark, 1998; Martens, 2016b). From a person's perspective, effective and efficient movement is only important because it allows individuals to participate in dispersed activities in space (Martens, 2016b). There would be no point in having no congestion and moving at high speed if there were no nearby activities in which the individual could participate.

In this sense, transport planning should pursue the objective of providing people with access to activities they value (Cervero, 2001; Martens, 2016a,b). The understanding of this objective by technicians, planners, and policymakers has contributed to accessibility planning gaining momentum. The accessibility approach reinforces the need for transport planning to occur integrated with land use planning and moves away from planning based merely on infrastructure provision and demand management towards a social policy perspective, more focused on people and their needs (Cervero, 2001; Lucas, 2012; Lucas *et al.*, 2016; Martens, 2006). The focus has shifted from minimising travel time to providing access for individuals to a variety of places/activities within a reasonable costs (Banister, 2008; Miller, 2018, 1999).

Considering that from a people perspective, transport planning should aim to provide opportunities for individuals to access desired activities, i.e. to provide accessibility, when transport planning fails to achieve its goal, individuals can be deprived of access and, consequently, of participation, becoming at risk of social exclusion. An individual is socially excluded if "(a) he or she is geographically resident in a society but (b) for reasons beyond his or her control he or she cannot participate in the normal activities of citizens in that society and (c) he or she would like to so participate" (Burchardt *et al.*, 1999, p. 229). Socially excluded individuals cannot access many of the essential opportunities in society, such as education, employment, and health. As a result, they suffer considerable economic and social costs (United Nations, 2016). Also, social exclusion makes a society not only less cohesive but also less safe (United Nations, 2016).

Although the accessibility concept was introduced in the 1950s (Hansen, 1959) and applied in transport studies related to social aspects in the 1970s (Black and Conroy, 1977; Wachs and Kumagai, 1973), it was only after the 2000s that its articulation with the social exclusion notion emerged (Social Exclusion Unit, 2003). After the report "Making the Connections: Transport and Social Exclusion" launched by the Social Exclusion Unit (2003), several studies on transport-related social exclusion have been published. The vast number of publications about the topic originated an increasing lack of conceptual clarity regarding what transport-related social exclusion (TRSE) and related concepts, such as transport disadvantage, transport poverty, accessibility disadvantage and accessibility poverty, actually mean.

Furthermore, the number of studies in the transport field concerned with issues related to equity and justice has grown in the last decade (Lucas *et al.*, 2016; Martens, 2016b; Pereira *et al.*, 2017; van Wee and Geurs, 2011; Vecchio and Martens, 2021). Some of these studies have looked at the distributional aspects of transport from the perspective of ethical theories (Lucas *et al.*, 2016; Martens, 2016b; Martens and Golub, 2012; Pereira *et al.*, 2017). Among these works, the interest specifically in Rawls' egalitarianism and Amartya Sen's Capabilities Approach (CA) stands out (Bantis and Haworth, 2020; Beyazit, 2011; Cao and Hickman, 2019; Hananel and Berechman, 2016; Lira, 2017; Martens, 2016b; Pereira *et al.*, 2017; Vecchio and Martens, 2021). Some authors argue that, compared to other justice and fariness approaches, the CA is one of the most appropriate to account for how individuals' wide diversity can affect their life chances (Luz and Portugal, 2021; Pereira *et al.*, 2017; Vecchio and Martens, 2021). It is worth noting that this dissertation intends to delve only into the issue of transport-related social exclusion, which is only one of the many aspects within the field of equity. From this perspective, ethical theories with a suficientarian approach, such as CA, are more appropriate than egalitarian approaches, such as Rawls' theory of justice. This is because social exclusion refers to the lack of a minimum of resources for individuals to be able to participate in the normal activities of the society in which they are inserted. This justifies the exclusive focus of this dissertation on Amartya Sen's theory. Despite the growing number of studies applying the Capabilities Approach to transport from an equity perspective, works that do so specifically from transport-related social exclusion are scarce (Luz and Portugal, 2021).

Many studies applying the Capabilities Approach to transport studies suggest understanding accessibility as a human capability (Bantis and Haworth, 2020; Cao and Hickman, 2019; Luz and Portugal, 2021; Oviedo and Guzman, 2020; Pereira *et al.*, 2017; Ryan *et al.*, 2015). This understanding suggests that the land use and transport components of accessibility are only resources, and the value of these resources will depend on individuals' abilities to convert them into travel and, consequently, access to and participation in activities they value (Hickman *et al.*, 2017; Luz and Portugal, 2021; Vecchio and Martens, 2021). Although beneficial to articulate the accessibility narrative theoretically, the idea of accessibility as a human capability is a much more complex and multidimensional concept than those used in conventional transport studies (Luz and Portugal, 2021; Pereira *et al.*, 2017; Vecchio and Martens, 2021).

In this sense, despite the wide range of accessibility measures developed over time, there is no accessibility measure available today that can perfectly capture all the participation options available to individuals. Also, there is no consensus on the best accessibility measures available, nor any agreement regarding definitions and operationalisation of these measures (Handy, 2020; Lei and Church, 2010; Malekzadeh and Chung, 2019). Most of the existing literature about accessibility measures tend to emphasise the factors that impact accessibility score but tends to ignore the relationship between these measures and the goals of accessibility, such as providing options for activity participation (Martens, 2016b). Given the tremendous popularity that accessibility has assumed in recent years, several measures have been created and applied in various fields of knowledge, such as geography, transport engineering, urban planning, and economics. Therefore, it is likely that not all accessibility measures developed are adequate to assess the risk of transport-related social exclusion.

Currently, several studies and public policy interventions are based on the assumption that greater accessibility inevitably leads to greater activity and, consequently, reduces the risk of social exclusion. Although this statement makes sense from a theoretical point of view, there is no consensus among the empirical evidence (Allen and Farber, 2020; Fransen *et al.*, 2018a; Merlin, 2015). Some articles found that accessibility levels are associated with higher trip making and activity participation (Allen and Farber, 2020; Calvo *et al.*, 2019; Koenig, 1980; Leake and Huzayyin, 1980; Lee and Goulias, 1997; Purvis *et al.*, 1996; Vickerman, 1974), while other studies found that this relationship is weak (Hanson and Schwab, 1987; Kitamura *et al.*, 2001) or not statistically significant (Ewing *et al.*, 1996; Handy, 1993). There were also studies that found mixed (Cordera *et al.*, 2017; Fransen *et al.*, 2018a; Kitamura *et al.*, 2001; Seo *et al.*, 2013; Thill and Kim, 2005) and negative effects (Williams, 1989). Also, previous studies about this relationship were concentrated in Global North contexts, were merely correlational and did not infer causality between accessibility and activity participation. This lack of consensus may suggest that it is not sure that policy interventions in terms of accessibility produce reliable results. In other words, the impact of policy interventions based on accessibility measures aimed to reduce TRSE may be overestimated or have the opposite effects to those expected.

1.2 Aims

The aim of this dissertation is threefold:

- The first is to develop a broad and detailed theoretical framework based on Capabilities Approach about how individuals may be prevented from travelling and accessing valued opportunities and how this may lead to social exclusion.
- The second is to provide an overview of the extent to which each of the widely used accessibility measures is suitable for assessing transport-related social exclusion phenomena from theoretical and practical perspectives.
- The third is to test the causal relationship of accessibility, measured using one of the most popular and straightforward accessibility measures, on activity participation level in a Global South context (São Paulo).

The first and second aims are addressed in chapters 2 and 3, while the third aim is addressed in chapter 4.

1.3 Dissertation Overview

This dissertation is organised into five chapters, the first of which is the introduction. Chapters 2, 3 and 4 are organised as articles. Therefore, it is likely that some key concepts to be repeated throughout those chapters. The repetition of such concepts is justified to guarantee each chapter's independence from the rest of the dissertation. As a consequence of the article form adopted, the research methods used in the dissertation are discussed in more detail in chapters 2, 3 and 4.

Chapter 2 provides a theoretical framework that will support the remainder of the dissertation. The proposed theoretical framework is based on an extensive and critical review of the literature on TRSE and articulates the Capabilities Approach proposed by Amartya Sen with the concept of accessibility. The chapter advocates for the notion of accessibility as a human capability and connects it with several related terms (e.g. transport disadvantage, transport poverty, potential mobility, motility, accessibility poverty, accessibility disadvantage) and with ten dimensions that TRSE can assume. The chapter concludes by discussing the theoretical and practical implications of adopting accessibility as a human capability notion and assessing TRSE from this perspective.

Chapter 3 draws on the theoretical framework on TRSE developed in Chapter 2 to derive ten theoretical criteria for assessing the suitability of accessibility measures to evaluate TRSE. In addition, based on the accessibility literature, two criteria are proposed to assess the ease of use and communicability of the accessibility measures. Based on the twelve criteria analytical framework, the chapter assesses 24 accessibility measures according to their adherence to the social inclusion goal and ease of use and communicability. The chapter concludes with a discussion on how and to what extent each of the widely used accessibility measures is suitable for assessing TRSE.

Chapter 4 provides empirical evidence on the relationship between accessibility and activity participation. Firstly, the chapter summarises the literature empirical evidence about the relationship between accessibility and participation in activities. Secondly, the mathematical relationship (the shape of the curve) between accessibility and participation in activities is discussed theoretically. Finally, a case study is conducted in the city of São Paulo to assess the causal relationship between both variables. The instrumental variable approach is used as an identification strategy due to the cross-sectional nature of the available data. The case study uses the cumulative opportunities measure to account for accessibility levels and assess the causal impact of accessibility on total, mandatory and discretionary activities.

Finally, chapter 5 summarises the dissertation and discusses the implications of the findings obtained for policy formulation and future research in TRSE.

Chapter 2

Understanding Transport-Related Social Exclusion Through the Lens of Capabilities Approach

Abstract

The chapter builds on the TRSE literature and investigates how the insights provided by the Capability Approach can help to inform inclusive transport planning. To address the literature lack of conceptual clarity, we provided a framework that considers how individuals may be prevented from travelling and accessing valued opportunities and how this may lead to TRSE. Ten different dimensions of TRSE that individuals may experience are suggested. Although some dimensions were already proposed in past work, we contributed to this framework by expanding their scope and proposing a new dimension. The chapter concludes that policies aimed at reducing TRSE should be concerned with increasing the capabilities of those in accessibility poverty to a sufficient level that enables individuals' participation in key opportunities of the society. We identified that not every accessibility measure is suitable for assessing TRSE, and the selection of measures must pay attention to their alignment with the idea of accessibility as a human capability. We recommend that conducting an aggregated analysis may be helpful to identify a suitable accessibility measure and to identify regions at risk of TRSE; however, to have a deep understanding of an individual's TRSE risk factors, a bottom-up analysis is necessary.

2.1 Introduction

Social exclusion has significant economic and social costs associated with renouncing the contribution of individuals and groups that cannot access critical opportunities in society, such as education, employment, and health (United Nations, 2016). Also, social exclusion presents political risks, as it reflects and sustains social tensions and is at the origin of many violent conflicts (United Nations, 2016). Individuals who are socially excluded are also those who inhabit the areas that are more vulnerable to natural hazards and disasters and are disproportionately harmed by them. Exclusion makes society not only less cohesive but also less safe (United Nations, 2016)

Over the last two decades, the number of studies concerned with the nexus between transport and social inclusion has increased dramatically. The report published by the Social Exclusion Unit (2003) was the watershed that put the theme of social exclusion on the transport policy agenda. Since then, several conceptual and review studies have been done addressing a variety of issues related to the transport-related social exclusion (TRSE) topic, such as the role of ICT in reducing social exclusion (Durand *et al.*, 2021; Kenyon *et al.*, 2002; Lucas, 2019); the relationship between mobility, accessibility, and social exclusion (Cass *et al.*, 2005; Preston and Rajé, 2007); the centrality of accessibility in the social inclusion and equity agenda (Farrington and Farrington, 2005; Farrington, 2007; van Wee and Geurs, 2011); the link between transport and well-being (Adeel *et al.*, 2016; Currie, 2010; Ma *et al.*, 2018; Oviedo and Sabogal, 2020); the relationship between social capital, transport and social inclusion (Currie and Stanley, 2008; Gray *et al.*, 2006; Schwanen *et al.*, 2015); the synergy between social exclusion and environmental justice in transport policies (Lucas, 2006); how TRSE concepts and definitions have been translated into policy and practice (Lucas, 2012); transport appraisal methods and social exclusion (Lucas *et al.*, 2016; van Wee and Geurs, 2011), and measures of TRSE (Kamruzzaman *et al.*, 2016; Pyrialakou *et al.*, 2016). This large amount of works originated a growing lack of conceptual clarity about what TRSE and its related terms actually mean (Arranz-López *et al.*, 2019).

Many have argued that the Capabilities Approach is the most appropriate fairness approach to express complex concepts (Bantis and Haworth, 2020; Hananel and Berechman, 2016; Martens, 2016b; Pereira *et al.*, 2017) and, therefore, to consider the broad diversity of individuals and how it interacts with transport and land use resources to affect people's opportunities (Vecchio and Martens, 2021). The number of studies interested in the application of Amartya Sen's Capabilities Approach (CA) in transport research also has increased recently (Beyazit, 2011; Cao and Hickman, 2019; Hananel and Berechman, 2016; Lira, 2017; Martens, 2016b; Pereira *et al.*, 2017; Ryan *et al.*, 2015, 2019; Vecchio and Martens, 2021) and the many distinct definitions of the related concepts generated varied operational applications (Vecchio and Martens, 2021).

This chapter builds on the TRSE literature and investigates how the insights provided by the Capability Approach can help to inform inclusive transport planning. We provide a broad and detailed critique overview of TRSE literature and bring together many of its concepts to tackle the current lack of clarity. We add to the state-of-the-art by providing a framework that considers how individuals may be prevented from travelling and accessing valued opportunities and how this may lead to each form of TRSE. Based on the past work, we suggest ten different dimensions of TRSE that individuals may experience. Although some categories were already proposed in past work, we contribute to this framework by expanding their scope and proposing a new dimension. We also identified that not every accessibility measure is suitable for assessing TRSE and recommend a strategy to identify a suitable one.

This chapter is structured as follows. Section 2.2 presents the research design. Section 2.3 and 2.4 define social exclusion, TRSE, and related terms (transport disadvantage, transport poverty, accessibility disadvantage and accessibility poverty). Section 2.5 connects the TRSE theory to the Capabilities Approach. Section 2.6 presents a conceptual framework about how accessibility as human capability components may interact to generate ten different forms of TRSE. Section 2.7 discusses the challenges of inclusive accessibility planning and makes recommendations to select an appropriate accessibility measure to assess TRSE. Lastly, Section 2.8 presents a discussion about some of the implications for TRSE research and policymaking and provides recommendations for future research.

2.2 Research Design

The materials reviewed in this chapter are primarily from articles published in journals until July 2021. The search strategy for the selection of relevant literature to this article's development was based on published papers in English with the following quotes - ("transport*" AND "social exclusion"), "transport-related social exclusion", and "transport disadvantage"– in the publication title, abstracts, and keywords for all time. The Scopus database was used to obtain relevant full-text literature pieces. After filtering by only papers published in journals, the search provided a total of 433 papers. These articles were then submitted to a "Citation" analysis in the VosViewer software to identify the literature's core articles on TRSE. The "Citation" analysis determines the papers' relatedness based on the number of times they cite each other. We filtered the 433 papers with at least ten links with the others in the group. To mitigate a selection bias of older documents, we use a lower threshold of eight links for articles published in the last five years and five links thresholds for papers published after 2016. After filtering the papers, 118 articles were left. These publications were read and analysed in more detail to examine whether the concepts, methods, and results revealed theoretical understandings related to TRSE. After a careful examination, 75 out of the 118 articles were included in the final literature selection. After that, we used a forward and backward snowball method to complement the systematic literature review. We identified 48 additional research pieces, including books, book chapters, papers, and reports. The final literature reviewed thoroughly in this chapter consists of 123 pieces of research.

2.3 Defining Social Exclusion

Social exclusion is a broad and complex concept that goes beyond economic and material issues (Church *et al.*, 2000; Hodgson and Turner, 2003; Schwanen *et al.*, 2015; Stanley and Vella-Brodrick, 2009). Despite the increasing use and apparent acceptance of the term social exclusion, there is still confusion about the relationship between social exclusion and poverty (Hodgson and Turner, 2003), and the terms are often used interchangeably (Cass *et al.*, 2005; Church *et al.*, 2000). Sometimes, the term refers to specific groups, such as the poor; other times, it refers to disadvantaged areas (Cass *et al.*, 2005). Therefore, it is necessary to distinguish between the concepts of social exclusion and poverty (Church *et al.*, 2000; Kamruzzaman *et al.*, 2016).

Poverty is generally understood as the lack of material resources (Kenyon *et al.*, 2002) and can be decomposed into absolute and relative poverty. Absolute poverty defines a minimum level of income, whereby an individual is classified as poor if he/she falls below this level. The main weakness in the definition of absolute poverty is that it fails to recognise different circumstances and thus the income needs of different individuals in the population, assuming that there is always a fixed level of basic needs (Kenyon *et al.*, 2002). The concept of relative poverty, on the other hand, suggests that people are poor relative to a standard of living experienced by other members of the society in which they live (Kenyon *et al.*, 2002). It allows different definitions of poverty for individuals in different circumstances and living at different times.

Social exclusion, on the other hand, is a broader and more complex concept than the redistributive poverty debate allows (Kenyon *et al.*, 2002), going beyond economic and material issues (Church *et al.*, 2000; Hodgson and Turner, 2003; Schwanen *et al.*, 2015; Stanley and Vella-Brodrick, 2009). Burchardt *et al.* (1999, p. 229) suggest that an individual is socially excluded if (a) he or she is geographically resident in a society but (b) for reasons beyond his or her control he or she cannot participate in the normal activities of citizens in that society and (c) he or she would like to so participate. Non-participation in society is related to the deprivation process, characterised as the lack of attributes that contribute to some king of suffering or relative disadvantage (Higgs and White, 2000). These attributes include, but are not limited to, income and material resources. This distinction between poverty and social exclusion allows us to acknowledge that poverty does not necessarily lead to exclusion; and that an individual can be excluded without being poor (Kenyon *et al.*, 2002; Preston and Rajé, 2007). Social inclusion, in turn, refers to "the process of improving the terms of participation in society for people who are disadvantaged" (United Nations, 2016, p. 20) and is both a process and a goal to be achieved. Promoting social inclusion requires tackling social exclusion by removing barriers to participation in society and actively "bringing people in", taking steps to facilitate such participation (United Nations, 2016).

The emphasis on poverty as the primary cause of exclusion implies that poverty reduction through redistribution is the solution to the social exclusion problem. According to Kenyon *et al.* (2002), this premise fails to recognise exclusionary factors unrelated to income, stating that poverty necessarily results in exclusion and that high-income people cannot be excluded. However, social exclusion can assume multiple dimensions, and the lack of material resources is only one of them (Casas and Delmelle, 2014; Kamruzzaman *et al.*, 2011; Kenyon *et al.*, 2002; Schwanen *et al.*, 2015).

While poverty is purely distributional and focuses on the outcomes of unequal access to material resources, social exclusion focuses on the processes of unequal access to participation in society (Kenyon *et al.*, 2002). In this sense, social exclusion is a dynamic process (Burchardt *et al.*, 1999; Hine and Mitchell, 2001; Kamruzzaman *et al.*, 2011; Preston and Rajé, 2007) in which individuals may regularly move in and out over time (Hodgson and Turner, 2003). Poverty and deprivation, on the other hand, are static outcomes at a given instant in time (Kamruzzaman *et al.*, 2016). Table 2.1 presents the relationship between social exclusion, deprivation, and poverty processes and outcomes.

Table 2.1: Social exclusion outcome and process concepts.

Dynamic Process	**Static Outcome**	**Indicator**
Impoverishment	Poverty	Income
Social Exclusion	Deprivation	Multidimensional

Source: Kamruzzaman *et al.* (2016)

While policies to alleviate poverty focus on taking people from the bottom up; the focus of social exclusion policies is on moving those who are excluded from participation in society from the outside (exclusion) to the inside (inclusion) (Kenyon *et al.*, 2002). Unlike (absolute) poverty, social exclusion is a relative concept (Kamruzzaman *et al.*, 2011; Stanley and Vella-Brodrick, 2009). A person cannot be considered socially excluded in isolation; a broader context of other individuals' activities needs to be considered (Schwanen *et al.*, 2015). This is evidenced by Burchardt *et al.*'s 1999 definition, cited previously, in which social exclusion depends on the "normal activities of citizens in that society".

An important issue related to the social exclusion notion is whether low/non-participation in society results from voluntary choices or not (Loader and Stanley, 2009; van Wee and Geurs, 2011). Burchardt *et al.* (1999) argue that individuals are not excluded by choice; that is, an individual is socially excluded if, for reasons beyond his or her control, he or she would like to and cannot participate in the normal activities of that society. In this way, the powerlessness and the denial of choice inherent in the discourse of social exclusion prevent the extension of the concept to those who are self-excluded because, in the process of self-exclusion, the person exercises the power of choice, which is denied to people who suffer social exclusion Kenyon *et al.* (2002).

The exclusion experienced by individuals results from a unique interaction between the dimensions and characteristics of exclusion specific to that individual's circumstances. These dimensions of exclusion are cumulative and reinforce each other (Schwanen *et al.*, 2015). Social exclusion is also somewhat circular, with social exclusion being both a cause of lack of personal opportunities and an outcome or a reason for lack of personal opportunities (Stanley and Vella-Brodrick, 2009). We then define social exclusion as a complex, multidimensional and cumulative process, resulting from the interaction of several factors, with a focus on resource and power relations between individuals, groups and the state (Hodgson and Turner, 2003; Kenyon, 2003; Kenyon *et al.*, 2002; Schwanen *et al.*, 2015). It involves the lack or denial of resources, rights, goods and services, and the inability of an individual, group or region, to participate in desired normal relationships and activities (Cass *et al.*, 2005) available to most people in a society, whether in economic, social, cultural or political areas. It affects not only the material and non-material quality of life but also life opportunities, choices and citizenship, and the equity and cohesion of society as a whole (Kenyon *et al.*, 2002).

A widely discussed issue in the literature about social exclusion is its quantification (Adeel *et al.*, 2016; Preston, 2009; Stanley and Vella-Brodrick, 2009). Despite some attempts at quantification (Burchardt *et al.*, 1999; Currie and Delbosc, 2010; Ma *et al.*, 2018; Stanley *et al.*, 2011), it cannot be suggested that one person is more or less excluded than another person due to the number of exclusionary characteristics they experience (Kenyon *et al.*, 2002; Stanley and Vella-Brodrick, 2009). Moreover, it is not a binary state, where one is excluded or not excluded (Shergold and Parkhurst, 2012), but rather a dynamic process characterised by different levels caused by a wide range of local and non-local processes (Schwanen *et al.*, 2015). Each individual or group will experience exclusion characteristics to different degrees and extents according to their circumstances. It is also emphasised that many exclusion characteristics are not quantifiable, e.g. powerlessness, self-esteem, isolation and perceptions governing individuals' choices (Schwanen *et al.*, 2015). The highlighted distinctions between poverty and social exclusion are summarised in Table 2.2.

Table 2.2: Some important distinctions between poverty and social exclusion

Poverty	**Social Exclusion**
Material resources	Participation in society
Distributional	Relational
Outcomes	Processess
Economic rights	Citizenship rights
Up from down	In from out
Uni-dimensional	Multiple dimensions
Easily quantifiable	Difficulty to quantify

Source: Kenyon *et al.* (2002)

The main result of social exclusion is the lack of participation, and deprivation indicators, such as income, low education, little political power, are only causes or risk factors for social exclusion. None of these indicators would be considered social exclusion if the individual, even with all the adverse conditions, could participate in the different dimensions that activities can take (Burchardt *et al.*, 1999).

2.4 Nexus of Social Exclusion and Transport

Several concepts are used to refer to the nexus between social exclusion and transport. There is no consensus about the most commonly used terms, including transport disadvantage, transport poverty, accessibility disadvantage, and accessibility poverty. In this sense, it is essential to define them and clarify how they relate to each other before going deeper into the transport-related social exclusion concept.

Transport disadvantage is defined by some authors as the difficulties to travel when needed (Currie, 2010; Denmark, 1998). Other authors broaden the understanding of the transport disadvantage to the problems in accessing opportunities because of difficulties of transport, that is, difficulties in potential mobility – defined as a person's ability to move through space (Kamruzzaman *et al.*, 2011, 2016; Marquet *et al.*, 2017; Martens, 2015; Oviedo and Guzman, 2020; Pyrialakou *et al.*, 2016; Vecchio and Martens, 2021; Xiao *et al.*, 2018). More "indirect" forms of transportation disadvantage, such as the relative lack of power to affect the formulation and governance of transportation policies (Denmark, 1998; Hodgson and Turner, 2003), high exposure to negative transport externalities such as traffic accidents, poor air quality, or excessive noise, is also mentioned in the literature (Schwanen *et al.*, 2015).

Although similar to the transport disadvantage concept, transport poverty is used to refer to a lack of resources related to transport that hinders an individual's potential mobility and, therefore, its ability to access opportunities (Groth, 2019; Jeekel and Martens, 2017; Martens, 2016a; Mattioli, 2017). It means that a person who experiences transport poverty cannot access key opportunities because he/she lacks access to adequate means of transport. Other definitions of transport poverty include the combined effect of transport disadvantage with social disadvantage (e.g., unemployment, low income, etc.), resulting in adverse outcomes like lengthy commutes and inaccessibility (Lucas, 2012). Also, the literature uses the transport poverty term to refer to the affordability of transport costs, and it is employed alongside other notions such as "transport affordability", "forced car ownership", and "car-related economic stress" (Mattioli *et al.*, 2018).

The terms accessibility poverty and accessibility disadvantage are centred on a more comprehensive interpretation of the notion of resources than the transport poverty and transport disadvantage (Jeekel and Martens, 2017). Accessibility poverty refers to a situation where an individual's level of accessibility is insufficient to provide access to key opportunities in a society, such as health care, employment, education, or social support networks (Lucas, 2012; Martens and Bastiaanssen, 2019). Accessibility disadvantage, in turn, refers to the difficulties of accessing normal opportunities in a society when needed. Difficulties or inability to access activities may be due to transport problems but may also be related to individual characteristics and land use patterns (e.g., when a person has a high level of potential mobility but lives in a remote location without activities). Kenyon *et al.* (2002, p.210-211), in their seminal paper, defined transport-related social Exclusion (TRSE) as:

> "The process by which people are prevented from participating in the economic, political and social life of the community because of reduced accessibility to opportunities, services and social networks, due in whole or in part to

insufficient mobility in a society and environment built around the assumption of high mobility."

From the TRSE definition of Kenyon *et al.* (2002), it is possible to establish some relationships between the TRSE notion and the concepts previously presented. First, TRSE is primarily about the lack of possibilities for participation in the community (society) and not necessarily about the resources available to a person (Jeekel and Martens, 2017). Second, TRSE occurs when accessibility disadvantage reaches a critical level (accessibility poverty), and systematic problems of access to opportunities prevent participation in society. Third, the problems in accessing opportunities may be due in whole or in part to difficulties in travelling (transport disadvantage) or insufficient (potential) mobility (transport poverty). Fourth, persons facing accessibility poverty are at risk of transport-related social exclusion (Jeekel and Martens, 2017).

Although the accessibility notion has been around for some time, its articulation with social inclusion emerged with UK policymakers in the early 2000s. The iconic document "Making the Connections: Transport and Social Exclusion" released by the Social Exclusion Unit (Social Exclusion Unit, 2003), brought about a new narrative of accessibility, changing the discourse from "ease of getting somewhere" to people's ability to reach and engage in normal activities in society (Farrington and Farrington, 2005; Farrington, 2007). The new narrative provided by Social Exclusion Unit (2003) directs attention to people, which is not surprising since, from a social inclusion perspective, people should be guaranteed participation in society rather than places (Martens, 2016a; Neutens *et al.*, 2010). Thus, the SEU report (2003) introduced "accessibility planning" into transport plans prepared by the English authorities (Shergold and Parkhurst, 2012) and influenced research in the area of social exclusion and transport worldwide (Lucas, 2012).

One may think that improving access to opportunities, and hence accessibility, means improving potential mobility, but this is likely to be a limited solution, not fully viable or sustainable (Bantis and Haworth, 2020; Bocarejo S. and Oviedo H., 2012; Farrington and Farrington, 2005; Gray *et al.*, 2006; Kenyon *et al.*, 2002; Lucas, 2006). Excessive mobility by private and unsustainable modes can increase social exclusion by contributing to the decline in public transport and widening the mobility gap in society (Denmark, 1998; Martens, 2006, 2016a; Pereira *et al.*, 2017). Furthermore, social exclusion does not necessarily mean immobility (Ureta, 2008), with some studies suggesting a relationship between TRSE and high levels of motorisation, such as the phenomena of "forced car ownership" and "time poverty".

The term "forced car ownership" (FCO) refers to the economic stress suffered by disadvantaged households who bear high costs relative to their income due to the involuntary choice to own, maintain and operate a car (Currie *et al.*, 2010; Currie and Senbergs, 2007; Pyrialakou *et al.*, 2016). Alternatively, households may choose to allocate enough money to other activities (considered essential) and reduce spending on 'non-obligatory' travel, e.g. leisure, visiting friends and family, restricting their activity spaces and, consequently, opportunities to participate Mattioli (2014); Pyrialakou *et al.* (2016). The phenomenon of 'forced car ownership' is linked with the sprawling, monocentric city model, in which household location decisions involve trade-offs between housing and transport costs, with low-income households being forced to live further away from employment/activities where housing is cheap, and in return accept higher transport costs (Delbosc and Currie, 2011b; Walks, 2018).

The "time poverty" hypothesis, on the other hand, relates to individuals who, due to the long distances travelled (in sprawling regions) to access jobs, spend a considerable portion of their time commuting and, thus, have little or no time to engage in other activities, feeling isolated or excluded from society. Currie and Delbosc (2010) and Currie *et al.* (2010) identified that this phenomenon is related not only to socially disadvantaged groups but also advantaged, high-income and economically active groups. Furthermore, Kamruzzaman *et al.* (2015), in a study conducted in rural Northern Ireland, identified highly mobile groups who emitted a significantly high level of CO2 but had low participation in society due to time poverty. This research clearly shows that more mobility can lead to increased CO2 levels and still not guarantee participation in society. It eliminates the idea that sustainability's environmental and social dimensions are necessarily conflicting (Kamruzzaman *et al.*, 2015; Lucas, 2006). High rates of unsustainable mobility are associated with negative externalities such as environmental degradation, high traffic accident rates and adverse public health impacts (Preston and Rajé, 2007) not necessarily reflect greater participation in society.

Although transport planning based on increasing flow speeds has improved accessibility for many of those who use private cars, it has neglected the condition of people who are poorly served by the current public transportation systems, with negative consequences for their access to destinations and their ability to participate in society fully (Lucas, 2012; Martens, 2016a; Pucci *et al.*, 2019; van Wee and Geurs, 2011; Vecchio and Martens, 2021).

In this sense, the notion of "mobility rights" is less powerful in articulating social inclusion than the notion of "accessibility rights" - to the extent that a minimum level of accessibility is required to meet the basic needs of individuals - since mobility is but one (albeit critical) way of achieving accessibility (Farrington, 2007; Pucci *et al.*, 2019). The discourse of "accessibility rights" does not conflict with the mobilities discourse because it acknowledges the "significant role that mobility plays, and will continue to play, in achieving the spectrum of people's needs for reaching and participating in activities, services, and opportunities" (Farrington, 2007, p. 327).

2.5 Framing Accessibility into Capability Approach

The interest in applying Amartya Sen's Capabilities Approach (CA) in transport research has increased recently (Bantis and Haworth, 2020; Beyazit, 2011; Cao and Hickman, 2019; Hananel and Berechman, 2016; Lira, 2017; Martens, 2016b; Pereira *et al.*, 2017; Vecchio and Martens, 2021). When compared to other transportation fairness approaches, the Capabilities Approach is better suited to account for the individuals' wide diversity, considering not only how transport and land use resources are distributed and interact with each other, but also how these affect people's opportunities differently depending on their characteristics, aspirations, and choices (Vecchio and Martens, 2021). The CA provides flexibility to express complex concepts (Bantis and Haworth, 2020; Hananel and Berechman, 2016; Martens, 2016b; Pereira *et al.*, 2017), being helpful to articulate a broader notion of accessibility that incorporates individuals' characteristics.

Individual freedom of choice and human agency are at the heart of the CA's concerns (Nussbaum and Sen, 1993). CA states that a person's well-being should be based on its real opportunities to do and be what they reason to value (Sen, 1995). Contrary to Rawl's egalitarian approach (Rawls, 1999), where the emphasis is on the primary goods, Sen argues that commodities or wealth people have provide only limited or indirect information about how well life is going (Sen, 2009). CA focuses on the well-being that individuals achieve because of the things they actually do and be, but also the things they could potentially do and be. CA's four notions are central in analysing this well-being: resources, the conversion function, functionings, and capabilities.

- Resources are the commodities and intangible goods available to a person to pursue the life they value. It depends on a person's characteristics, background, and social-spatial context. Resources are the "means to achievement" (Sen, 1995).
- The conversion function determines the possibility of converting resources into freedoms and conveying the personal, social, and environmental conditions that form its life experience (Sen, 1995).
- Functionings are the various things a person may value 'being and doing,' such as being well-nourished, having shelter, and participating in political decisions (Sen, 1995, 2009).
- Capabilities refer to the set of functionings (the combinations of beings and doings) that a person has effective access to. Each capability is "whatever [people] are able to do and be in a variety of areas of life" (Nussbaum and Sen, 1993, p.2). In other words, capabilities are the set of opportunities and freedoms available for individuals to choose and to act (Nussbaum, 2011; Sen, 2009).

Transport research based on CA is diverse in its theoretical conceptualisations, reflected in the various understanding of the CA notions and, consequently, different operational implications.Although mobility is not addressed directly by the main theorisations of CA (Vecchio and Martens, 2021), some transport researchers consider it a capability (Beyazit, 2011; Hananel and Berechman, 2016; Ryan *et al.*, 2019). This school of thought views mobility as "being physically, socially and financially able to move from one place to another and interact within society or with different societies" (Beyazit, 2011, p.123), an understanding that is close to the concepts of motility ((Flamm and Kaufmann, 2006; Kaufmann, 2002) – defined as "the way in which an actor appropriates the field of possible action in the area of mobility, and uses it to develop personal projects" (Kaufmann, 2002, p.3)- and potential mobility (Martens, 2015)

A different conceptualisation of CA in transport research is accessibility as a human capability. This line of thought defines accessibility similarly to the accessibility narrative brought about by TRSE studies: "persons‘ possibility in engaging in a variety of out-of-home activities" (Martens, 2016a, p.137). This definition comprises the idea of a "person's ability to move through space" but goes further considering a person's ability to translate resources into activity participation (Martens and Golub, 2012; Pereira *et al.*, 2017; Vecchio and Martens, 2021). Since we are concerned with ensuring not just that people move through space but that they reach and participate in activities to be socially included, the idea of accessibility as a capability makes more sense than mobility as a capability to inform social inclusion. The notion of accessibility as a human capability incorporates the land-use component and considers how it interacts with the transport systems components to enhances people's capabilities (Pereira *et al.*, 2017). While accessibility captures the people's possibilities to participate in valued activities, mobility is a means (Bantis and Haworth, 2020; Cao and Hickman, 2019; Oviedo and Guzman, 2020; Ryan *et al.*, 2015), but it is not the only one, some accessibility may be acquired virtually.

In the accessibility as a human capability approach, resources comprise a wide variety of tangible and immaterial means, particularly related to transport systems and land use, that affect a person's mobility and accessibility directly or indirectly (Vecchio and Martens, 2021). The value of these resources will depend on the social, environmental and economic conditions and individuals' ability (conversion function) to convert them into functionings they value. Functionings are what the individuals actually do and how, reflected by their travel behaviour and activities participation pattern (Hickman *et al.*, 2017). The individual's capabilities is its accessibility, represented by the freedom to choose from different potential functionings (ways of moving around and possibilities of activity participation) (Hickman *et al.*, 2017). The individual's well-being, in turn, is shaped by his capabilities (accessibility) and their functionings (travel and activity participation) (Vecchio and Martens, 2021).

The accessibility as a human capability works as a reinforcing cycle. While individuals‘ ability to convert resources into actual participation (functionings) influences their well-being, the functionings realised, and well-being achieved from them contribute to improving their conversion function and, consequently, their capabilities (Figure 2.1). For example, individuals that access and participate in higher education (functionings) can get qualified (conversion function) to participate in an employment activity close to their residence that they could not before (capability). Alternatively, elderly individuals who access a park close to their home for exercise (functioning) may have better health (well-being) and face fewer problems when boarding public transport vehicles (conversion function).

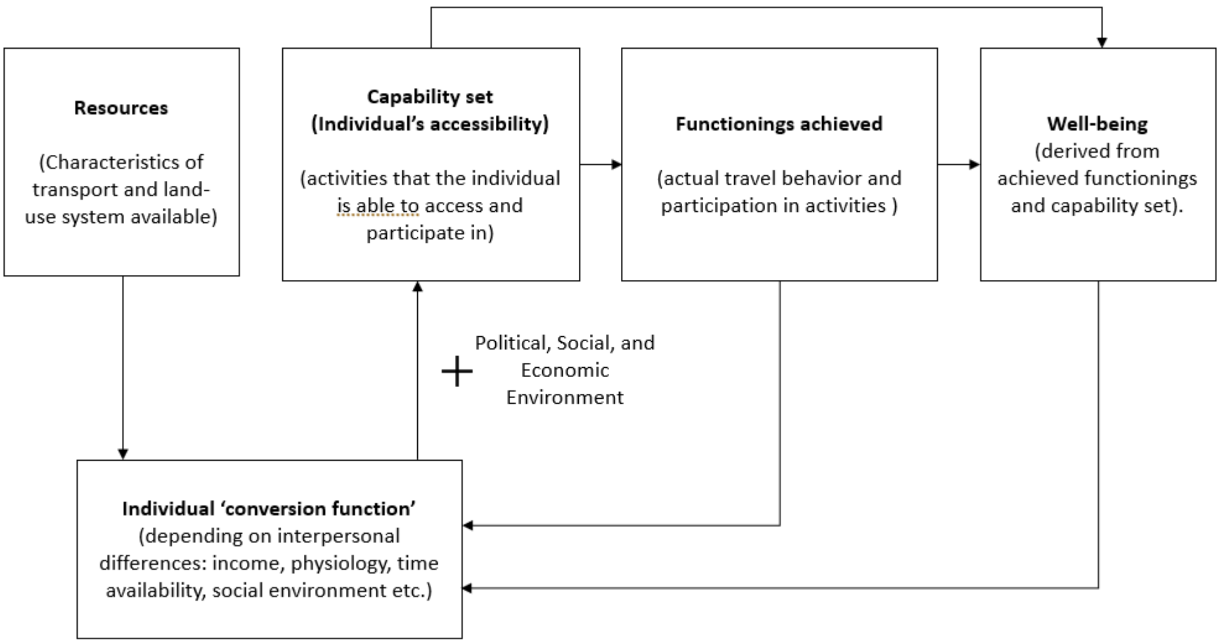


Figure 2.1: Accessibility as a Human Capability

Source: Author's elaboration

Transport planning approaches aimed to mitigate social exclusion often fetishise resources as the personification of advantage (Nussbaum, 2011; Pereira *et al.*, 2017). These approaches ignore how people's ability to convert land-use and transport-related resources into capability and well-being is affected by contingencies, such as personal characteristics, physical environment, and cultural norms (Pereira *et al.*, 2017).

The CA is particularly interested in promoting minimum levels of capability, which is crucial for equality of opportunities and freedom to do things vital for survival and later development (Nussbaum, 2011; Pereira *et al.*, 2017). This idea shares sufficientarian concerns discussed by some authors (Lucas *et al.*, 2016; Martens, 2016b; Pereira *et al.*, 2017; van Wee and Geurs, 2011; Vecchio and Martens, 2021), which presupposes that everyone should be well off up to a given minimum threshold sufficient to meet their basic needs and ensure their well-being (Lucas *et al.*, 2016). Weak sufficientarianism suggests that improvements for people below the threshold are preferred, while strong sufficientarianism implies that transport policy should be based on preventing accessibility poverty first and foremost (Meyer and Roser, 2009; van der Veen *et al.*, 2020). Public policies aimed to reduce TRSE must be concerned not only with providing a minimum level of access to essential activities (sufficient functionings) to individuals but also providing a reasonable level of freedom to them choose what they want "to do and be" (sufficient capabilities) (Nahmias-Biran *et al.*, 2017; Pereira *et al.*, 2017; Vecchio and Martens, 2021).

2.6 Accessibility as a Human Capability and the TRSE Dimensions

The idea of accessibility as a human capability has two separable but interacting components that we named spatial resources and individual's conversion function. These components are derived from traditional accessibility components: transportation, land use, temporal, individual, and cognitive (Geurs and van Wee, 2004; Lucas, 2012). The spatial resources component refers to the more macroscopic view of accessibility. It comprises two subcomponents: land-use patterns and transport systems and their respective temporal restrictions. The individual's utilisation function component of accessibility refers to a person's perceptions and abilities to convert spatial resources into access to activities, given their interaction with external factors, the social, economic, and political environment. It incorporates the individual's temporal and cognitive restrictions.

The interaction of spatial resources with the individual's conversion function and the external environment may expand or limit the individual's capabilities. When the limitation of individuals' capabilities reaches a critical level (accessibility poverty), and systematic problems in accessing opportunities prevent their participation in the normal activities of citizens in their society, they become transport-related socially excluded. Individuals may face different forms of TRSE depending on the barriers to participation that emerged in the interaction process between the spatial resources, individual conversion function, and external environment (Figure 2.2).

Several studies have proposed dimensions of TRSE. The first study in this sense was that of Church *et al.* (2000), who proposed seven dimensions: physical exclusion, geographical exclusion, exclusion from facilities, economic exclusion, time-based exclusion, fear-based exclusion, and space exclusion. Hine and Mitchell (2001) proposed five dimensions: Physical, Economic, Temporal, Spatial, and Psychological. The spatial dimension of Hine and Mitchell (2001) corresponds to the geographical and space-related dimensions of Church *et al.* (2000), and the psychological dimension relates to fear-based exclusion. Cass *et al.* (2005) identified four dimensions of access related to social exclusion: Economic, Physical, Temporal, and Organisational. The first three dimensions of Cass *et al.* (2005) are quite similar to those of Church *et al.* (2000) and Hine and Mitchell (2001). The fourth organisational dimension refers to the ability to use the different modes of transport in terms of suitable and convenient timetables, network structure, the quality of the experience, frequency, reliability, and punctuality. Yigitcanlar *et al.* (2019), in turn, considered six dimensions, five that are pretty similar to those presented by other authors, and the informational dimension, which refers to the availability of information for the use of public transport. Finally, Benevenuto and Caulfield (2019) proposed eight dimensions of social exclusion, the seven already proposed by Church *et al.* (2000) plus social position-based exclusion.

Based on their work, we suggest ten different dimensions of TRSE to describe as accurately as possible the different types of TRSE experienced by individuals. Although most categories received the same name as in the cited works, we contribute to this framework by expanding many of their scopes. Also, we propose a new category that was not mentioned in past work, the digital divide exclusion.

We propose a framework that connects the idea of accessibility as human capability and its related terms with the ten TRSE dimensions (Figure 2.2). This framework, together with the one presented in Figure 2.1, allows consideration of how each individual may be prevented from travelling and accessing valued opportunities and how this may lead to each form of TRSE. In Figure 2, the interaction between land-use and transport systems defines the spatial resources notion. The interaction between transport resources, individual's conversion function, and the political, social, and economic environment represent the concepts of potential mobility, mobility as a capability, and motility. If we add the land use component to the latter, we obtain accessibility as a human capability. Depending on how this interaction process occurs and the shortcomings in these building blocks, TRSE may take different forms. The descriptions of the ten TRSE dimensions are presented below. It is important to note that these ten dimensions are interrelated and may overlap in many aspects.

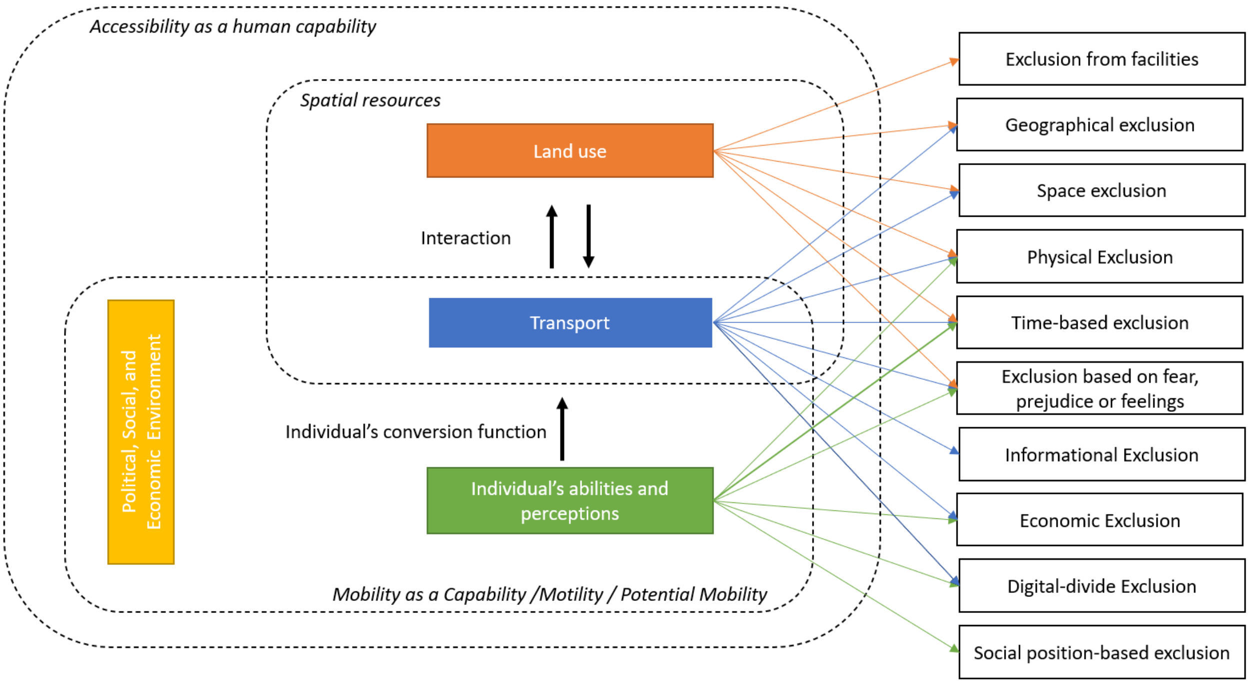


Figure 2.2: Relationship between accessibility as human capability components and TRSE dimensions

Source: Author's elaboration

Exclusion from facilities occurs due to the absence or distance to key opportunities such as employment, healthcare, schools, shops, or leisure services from where the individual lives. It may also occur when opportunities that can be accessed by public transport are not suitable for the individual(Church *et al.*, 2000). Increased diversity of activities offers opportunities to reduce the need for investment in services and employment outside the CBD, with subsequent impacts on distance, travel time, and the viability of modes such as public transport, walking, and cycling (Ma *et al.*, 2018). More diverse areas allow individuals to reach activities walking and avoid expenditure with private car ownership (Ma *et al.*, 2018; van Wee and Geurs, 2011).

Geographical exclusion occurs when a person's residence location prevents him/her from accessing transport services, or the transport system does not connect to the places that the person wants to access. People living in regions distant from CBD in monocentric cities or activities are more likely to be accessibility disadvantaged (Delbosc and Currie, 2011c; Guimarães *et al.*, 2019; Jaramillo *et al.*, 2012). The low urban density is at the heart of the problem Currie (2010); Marquet *et al.* (2017); Pyrialakou *et al.* (2016). In dispersed land-use patterns, where the predominant mode of transport is the bus, the physical layout of the roads may restrict the efficient provision of services Currie (2010). The transport network's spatial coverage and connectivity are also factors that limit individuals‘ capabilities set Casas and Delmelle (2014); Church *et al.* (2000); Engels and Liu (2011); Kamruzzaman and Hine (2012); Shergold and Parkhurst (2012). Also, the emergence of new mobility services may cause a lock-out of places (ex: sparsely populated and remote areas) where these services cannot be accessed due to non-operability Groth (2019); Lucas (2019). Other elements of the built environment, such as connectivity of streets and sidewalks, sidewalks, and bicycle paths infrastructure, may influence the ease of access Guimarães *et al.* (2019); Kenyon (2011); Ma *et al.* (2018); Oviedo and Sabogal (2020).

While in developing countries, the lack of transportation and local activities force populations to travel long distances on foot (Lucas, 2011; Ureta, 2008), in developed countries, the effect is "forced car ownership" Carroll *et al.* (2021); Currie *et al.* (2010); Mattioli (2014). Excessive dependence on walking as the primary means of transport can limit participation in other essential activities. Similarly, the economic stress caused by "forced car ownership" can lead to transport poverty and limit the number of trips to key opportunities. The lack of spatial resources is not equally or randomly distributed throughout society but follows well-defined patterns of structural social inequality (Bocarejo S. and Oviedo H., 2012; Jaramillo *et al.*, 2012; Lucas, 2011; Ureta, 2008; Xiao *et al.*, 2018) The locations with the worst levels of spatial resources are also those with the worst socioeconomic conditions (Jaramillo *et al.*, 2012; Xiao *et al.*, 2018).

Space exclusion occurs when security or space management of some public and private spaces discourages certain groups from using public and quasi-public transport spaces (e.g., first-class waiting rooms at stations) or certain areas (e.g., gated communities or areas of control militias). Certain types of surveillance and management of public transport spaces can weaken any sense of ownership amongst marginal groups (Church *et al.*, 2000).

Physical and cognitive exclusion occurs when transport systems or the built environment may impose physical and cognitive barriers to individuals. Physical and cognitive difficulties in accessing transport and activities are widely cited in the literature as factors that can restrict an individual's capability set (Casas, 2007; Casas and Delmelle, 2014; Currie and Delbosc, 2010; Delbosc and Currie, 2011b,d; Denmark, 1998; Engels and Liu, 2011; Groth, 2019; Hine and Grieco, 2003; Hine and Mitchell, 2001; Kamruzzaman and Hine, 2012; Lättman *et al.*, 2016; Ma *et al.*, 2018; Pereira *et al.*, 2017; Shergold and Parkhurst, 2012; Social Exclusion Unit, 2003). Among the factors that may prevent individual's to access and use transport and activities are the inability to drive, design of public transport vehicles, lack of adapted equipment for disabled people, saturated vehicle occupancy, inability to read timetable information, inadequate sidewalks. These are more frequently faced by the elderly, disabled, and illiterate. Difficulties include a deterioration in eyesight and hearing, poor coordination and slowed reactions, decreased and slower movements, and problems related to medication use (Denmark, 1998; Luiu and Tight, 2021). They also present problems with balancing due to jerky stops and starts of vehicles, crowd movement, the physical impact, long walking distance to activities and public transport stops, and lack of adapted seats and vehicles (Denmark, 1998). McCray and Brais (2007) suggest that because women play multiple roles and, even nowadays, are primarily responsible for child care, they are also likely to face urban and vehicle design barriers when travelling accompanied by children or with baby carriages. Regarding the built environment, poor pedestrian infrastructure may increase the risks of falls and stumbles for the elderly and physically disabled and, thus, limit accessibility (Ma *et al.*, 2018; Shergold and Parkhurst, 2012). The dependence on third parties of some disabled and older people limits the freedom of movement of these groups (Currie *et al.*, 2010).

Time-based exclusion occurs when the low frequency of the transport system, lack of punctuality, or person's demands on time, such as work, child and elderly care duties, or other commitment may limit travel opportunities and imply the possibility to travel only at times when there is little or no transport services and activities available. The time people spend accessing, waiting for transport and travelling may limit their access to activities. It may be related to the frequency of service, network design, the number of transfers, operational speed, and distance to activities(Bocarejo S. and Oviedo H., 2012; Casas and Delmelle, 2014; Delbosc and Currie, 2012; Dharmowijoyo *et al.*, 2020; Farber and Páez, 2011; Guimarães *et al.*, 2019; Lucas, 2011; Yigitcanlar *et al.*, 2019). Excessive time spent to access activities may lead to time poverty, where travel is so time-consuming that there is little or no time left for other essential activities (Dharmowijoyo *et al.*, 2020; Farber and Páez, 2011). Another issue to consider is the temporal variability of spatial resources (Fransen *et al.*, 2015; Geurs and van Wee, 2004; Kamruzzaman *et al.*, 2011; Lättman *et al.*, 2016; van Wee and Geurs, 2011). The variation in the frequency of transport services and the working hours of facilities throughout the day and week can limit access during specific periods, such as weekends and off-peak periods (Kamruzzaman and Hine, 2012).

Exclusion based on fear, prejudice, or feelings refers to the fear of crime and the perception of insecurity or prejudice that makes people avoid certain places (e.g., a particular neighbourhood, a bus stop). Also, aspects such as quality of the transport mode, safety during the journey and security to access to transport stations, cordiality of service providers influence the feeling about public transport and the perception of it as an option for travelling (Casas and Delmelle, 2014; Guimarães *et al.*, 2019; Lättman *et al.*, 2016; Lucas, 2011). Feelings about built environment elements, such as neighbourhood aesthetics, public lighting, may influence the ease of access to activities (Guimarães *et al.*, 2019; Kenyon, 2011; Ma *et al.*, 2018). The TRSE literature acknowledges that are more likely to face this form of exclusion are the women and elderly. Women face concerns about personal security and harassment when accessing public transport stops (Adeel *et al.*, 2016; Casas and Delmelle, 2014; Guimarães *et al.*, 2019; Hine and Grieco, 2003; McCray and Brais, 2007). Overcrowding during travel is also a potential impediment, as their safety may be compromised by the risk of being sexually harassed by other passengers Adeel *et al.* (2016); Casas and Delmelle (2014); Guimarães *et al.* (2019). The elderly frequently face the social disapproval that comes with slowing the movements of others during boarding and getting off public transport vehicles Denmark (1998).

Informational exclusion refers to the lack of available information on public transport and destination options that prevent individuals from planning their journey and, therefore, limit its use (e.g. lack of travel information at public transport stops, lack of information about the location of public transport stops, and lack of information about interruptions of service) (Casas and Delmelle, 2014; Lättman *et al.*, 2016; Lucas, 2011; Yigitcanlar *et al.*, 2019).

Economic exclusion occurs when the monetary costs of travel prevent people from travelling or restrict their access to destinations around their homes or mandatory activities. Most of the studies related to TRSE have identified poverty, low income, and unemployment as factors that prevent or limit individuals from accessing transport, thus compromising their participation in society (Bocarejo S. and Oviedo H., 2012; Casas, 2007; Currie and Delbosc, 2010; Denmark, 1998; Kamruzzaman and Hine, 2012; Kenyon *et al.*, 2003; Lucas, 2011; Ma *et al.*, 2018; Mattioli, 2014; Oviedo and Sabogal, 2020; Social Exclusion Unit, 2003; Tao *et al.*, 2020; Ureta, 2008; Walks, 2018). Low income and poverty have different effects on developed and developing countries. In developed countries, the impediment to using a particular transport mode can often be overcome by another less favourable but affordable, such as a car; even if it means spending a disproportionate percentage of the family budget on buying, owning, operating, and maintaining the vehicle (Currie and Delbosc, 2010; Mattioli, 2017; Pyrialakou *et al.*, 2016; Walks, 2018). On the other hand, the impediment to travel and access activities in developing countries is often absolute. If one cannot travel by motorised transport, the journey will be made on foot or will not be made at all (Lucas, 2011; Ureta, 2008). The limited budget requires prioritisation of essential activities such as employment, education, and the maintenance of the house, and other essential activities to inclusion, such as leisure, visiting friends and relatives, are excluded (Lucas, 2011; Ureta, 2008).

Digital-divide exclusion occurs when the lack of digital connection or inability to use appropriate ICT may prevent individuals from using app-based transport systems. Difficulties in using appropriate ICT are critical elements limiting individuals‘ access to smart mobility (Groth, 2019). Vulnerable populations have considerably lower access to the "smart mobility ecosystem", including bank accounts, and remain disproportionately cash-dependent and face mobile data limitations (Golub *et al.*, 2019).

Social position-based exclusion refers to the prevention from moving in public spaces due to censure, social control, or any other restriction based on one's social position (e.g., gender, race, nationality, age, ethnicity, caste, religion). A group likely to face this kind of exclusion is the migrants (Lauby, 2019; Ozkazanc, 2021). Because of a lack of language skills, migrants and refugees may face problems reading and understanding public transportation instructions and following the timetables (Ozkazanc, 2021). Some authors also identified the group of young people as one that might face accessibility disadvantage because of its characteristics (Denmark, 1998; Hine and Mitchell, 2001; Kenyon *et al.*, 2003; Lauby, 2019; Ma *et al.*, 2018; Social Exclusion Unit, 2003). There are concerns about the independence and safety of this group travelling unaccompanied by public transport, cycling, or walking. Without transport or safe alternatives, young people may be denied the opportunities and services enjoyed by many of their peers (Denmark, 1998).

2.7 The TRSE Assessment

Because TRSE is a complex phenomenon resulting from the interaction between several factors, its assessment is challenging. The appeal of using accessibility as a human capability in inclusive transport policies inevitably implies the need to develop and apply appropriate accessibility measures to assess the individual's capabilities. The notion of accessibility as a human capability is a more complex and multidimensional concept than those used in transportation studies (Pereira *et al.*, 2017; Vecchio and Martens, 2021). There are no accessibility measures that can fully capture all the nuances that influence an individual's capabilities. No matter how much of these nuances are considered in the accessibility measurement for the population, it is likely to give at best an approximation of people's capabilities.

The literature on accessibility measures emphasises the factors that shape accessibility but tends to ignore the relationship between these measures and the goals of accessibility (Martens, 2016b) and, consequently, social inclusion. However, the distributional outcomes of a given transportation policy will be considerably influenced by the accessibility measure chosen (Martens and Golub, 2012; Neutens *et al.*, 2010). In this regard, the accessibility measures used to assess TRSE should be carefully chosen and connected with the social inclusion goals as well as the theoretical concerns discussed earlier in this work (Curl *et al.*, 2011; Geurs and van Wee, 2004; Martens and Golub, 2012; Neutens *et al.*, 2010).

Because there are no perfect accessibility measures that entirely comprise all the factors that influence an individual's capabilities, researchers should at least avoid existing measures that may theoretically conflict with the idea of accessibility as a human capability. Considering that the goal is to enable individuals' participation in the key activities of society, measures that do not account for all possible opportunities in which individuals can engage are not recommended. In this sense, infrastructure-based accessibility measurements, space-time measures that account for the volume of space-time prism, and potential path area can be discarded. Another problem of space-time measures is the impossibility to account for mandatory activities, such as employment, since the space-time prism is established based on the all spatio-temporal paths that an individual can take given its fixed activities (Hägerstrand, 1970; Miller, 1999).

Planning activities based on utility measures also may lead to a counterintuitive distribution of resources from a social perspective. This distorted distribution arises from the fact that a person can adjust his/her expectations according to his or her life situation (Martens, 2016b; Martens and Golub, 2012; Sen, 2009). If utility is adopted as a benchmark for distributing transport resources, people with expensive preferences (see Martens and Golub (2012)) would have a higher threshold of sufficient accessibility. In this scenario, advantaged people would have to receive more resources to obtain the same level of welfare as disadvantaged individuals.

Accessibility measures that adopt a maximisation strategy – they consider only the most advantageous activity for the individual – are not recommended to assess the TRSE risk (Martens and Golub, 2012). This kind of measure fails to assess the set of viable opportunities for individual participation. The maximisation rule is restrictive and leaves little room for other decision rules that people may adopt when selecting activities (Neutens *et al.*, 2010). Place-based measures focused on minimum distance or time, and some Burns-Miller space-time measures fall into this category.

Accessibility measures based on the actual observed behaviour of individuals also violate the idea of accessibility as a capability. People are not interested only in the actual functionings they attain but also in the range of functionings they could potentially achieve (capabilities) (Martens, 2016b; Pereira *et al.*, 2017; van Wee, 2016; van Wee and Geurs, 2011). Activity-space and gravity measures with a decay function with parameters calibrated using observed travel data replicate biases (Handy and Niemeier, 1997) and compromise identifying opportunities individuals could potentially access. Such measures are problematic as they suggest that individuals can access only activities within a distance or area that they access daily. It may suggest that an individual's capabilities are smaller than they actually are. For example, a person who carries out all his/her daily errands in places close to their residence because he/she lives in a place well served by facilities but can access and participate in activities much further away from their home.

A better alternative to calibrate and define activity-space and gravity measures using decay function is basing on the individual's cognitive feasible opportunities set (Kwan and Hong, 1998). Many studies assume that a feasible set of opportunities is so small that the alternatives outside the distance or time threshold are not relevant to the individual. On the other hand, other studies assume that the feasible opportunity set is so vast that many of the alternatives contained therein are not perceived as possible to be accessed by the individual. In this sense, two aspects are essential in this calibration process: spatial knowledge or familiarity with various city areas and preference or aversion for specific locations.

Although we should focus the accessibility analysis on the potential of what people can achieve (capabilities), the measurement of functionings (actual travel behaviour and activity participation) may be a good way to understand the appropriateness of accessibility measures to assess TRSE. We are not interested in the trips distances for the definition of decay function parameters or the size of activity space, but rather in the quantity and quality of the trips and activities in which one participated. It is expected that higher levels of accessibility (capabilities) are related to participation in more and/or better activities (functionings). If we test this relationship at the individual level, some individuals are likely to have high capabilities and not undertake trips and participate in activities because of their own choice. However, if we conduct an aggregated analysis of the whole population or group of individuals, this relationship must be valid. In this sense, a good accessibility measure must be, at least in part, related to the quantity and quality of the trips and activities. Otherwise, they will not be adequate to assess TRSE and may generate misleading results.

Some studies that examined the relationship between activity participation and travel behaviour with accessibility found that a positive relationship exists (Allen and Farber, 2020; Fransen *et al.*, 2018a; Koenig, 1980; Thill and Kim, 2005; Vickerman, 1974), while other studies found that this relationship was weak or not statistically significant (Dalvi and Martin, 1976; Ewing *et al.*, 1996; Hanson and Schwab, 1987; Kitamura *et al.*, 2001). This lack of agreement in the literature may suggest that not every accessibility measure reflects the individual's capabilities and, therefore, not every measure is appropriate to assess the risk of TRSE. Alternatively, it may also suggest that accessibility measure choice must vary according to the context of analysis.

In this sense, the aggregated analysis between the relationship of accessibility measure and travel behaviour and activity participation may help select a measure that really depicts individuals' capability set. Also, an aggregated accessibility analysis may be helpful to identify TRSE cases due to spatial resources issues, such as poor transport systems or lack of activities. However, this kind of analysis may provide little insight into the individual's conversion function limitations. Such a deep understanding can only be achieved through an approach that starts from the individual as the unit of analysis. TRSE and the accessibility as human capability is fundamentally an individual notion and not always spatially clustered Hine and Grieco (2003).

2.8 Discussion and Conclusions

Framing accessibility in the CA approach removes the policy focus on resource distribution. Accessibility as a human capability recognises the diversity of individuals' needs and preferences and their respective capabilities to convert spatial resources into results they value. Such conceptualisation provides the basis for a pragmatic approach of CA in inclusive transport planning. By sharing the sufficientarianist ideals, the notion of accessibility as a human capability combines accessibility needs with the idea of social rights (Pereira *et al.*, 2017) – what Farrington (2007) called 'accessibility rights' – to the extent that a minimum level of accessibility is required to meet the basic needs of individuals. In this sense, public policies aimed at tackling TRSE should be founded on the concept of accessibility as a human capability, with strong sufficientarianism principles to prioritise and ensure a minimal level of capabilities for those in accessibility poverty. Adopting minimum accessibility requirements in practice would facilitate the implementation of normative criteria that can guarantee minimum accessibility standards for the entire population, preventing people from being denied to participate in society (Arranz-López *et al.*, 2019). Furthermore, accessibility thresholds can provide policymakers with an understanding of how much accessibility is needed to meet the fundamental needs of the greatest number of people (Bertolini, 2017).

Nevertheless, there are some concerns related to the minimum level of accessibility. Should this level be a universal or relative concept? Should this be derived from our creation of value concerning what we as a society, academia, or policymakers see as just or even appropriate? Or is it a universal concept that is independent of our vision as a society? What types of activities should have a minimum level of access? Below what threshold does it imply a problem that legitimises or suggests the need for policy interventions (Farrington, 2007; Lucas *et al.*, 2016; van Wee and Geurs, 2011)? The definition of what a "normal level" of accessibility is and when the accessibility is below this threshold remains a practical and philosophical issue in TRSE literature and deserves further research (Arranz-López *et al.*, 2019; Lucas, 2012; Lucas *et al.*, 2016; Pereira *et al.*, 2017; Pucci *et al.*, 2019; van der Veen *et al.*, 2020).

We advocate that the idea of a sufficient level of accessibility should be global-local (Farrington and Farrington, 2005). The concept abstracts particular circumstances; that is, all societies need a minimum level of accessibility, but its achievement will depend on specific local requirements. The relevance of activities will vary according to the political, economic, and social norms in that society and, therefore, participating in society will differ from society to society. Its definition is an explicitly normative process and demands a political decision taken through a genuine political and democratic process (Pereira *et al.*, 2017). Farrington and Farrington (2005) highlight that relativism, in this case, is inevitable and enriches the concept of accessibility since it recognises the different ways in which values can impact spatially and culturally accessibility needs in society. By making this choice explicit and a significant part of the process, the definition of the minimum level of accessibility can be made transparent instead of being hidden in technical assumptions (van der Veen *et al.*, 2020).

We proposed a framework that relates the notion of accessibility as a human capability and its related terms with ten TRSE dimensions. We suggest that accessibility as a human capability works as a reinforcing cycle. Individuals' capabilities set influences their well-being, and the functionings achieved, and well-being attained from them improve their individual conversion function and, consequently, their capabilities. The proposed framework allows consideration of how each individual may be prevented from travelling and accessing valued opportunities and how this may lead to each form of TRSE can take. Based on the past work, we suggest ten different dimensions of TRSE that individuals may experience. Although most categories have already been defined in the literature, we contribute to this framework by expanding their scope and proposing a new dimension: the digital divide exclusion.

The concept of accessibility as a human capability is more complex and multi-faceted than those applied in transportation research. Since there are no accessibility measures that can fully capture an individual's capabilities, researchers will need to use measures that represent the best proxies currently available and do not violate the theoretical aspects of the idea of accessibility as a human capability. In this sense, many categories of accessibility measures were discarded, for example, those based on utility, maximisation strategies, calibrated and defined based on observed travel behaviour, and those that do not account for all possible opportunities in which individuals can engage. We suggest that an alternative for the definition and calibration process of activity space and gravity-based measures is to based on the cognitive feasible opportunity set. However, the measures will need to be individually specified.

Although we are interested in what people can potentially achieve, we suggested that measuring what they actually do (actual travel behaviour and activity participation) may be a good way to understand which accessibility measures are more appropriate to assess TRSE. It is expected that higher levels of capabilities are related to higher levels of activity participation, and accessibility measures that fail to establish a valid relationship between those are not appropriate to assess TRSE. The literature that empirically assessed the relationship between accessibility and trip generation and activity participation has not yet reached a consensus on which accessibility measures are more appropriate to assess the risk of TRSE. It may suggest that not every accessibility measure reflects the individual's capabilities and that the choice of accessibility measure is likely to vary according to the analysis context.

In this sense, we recommend that planners conduct an aggregated analysis to check if the accessibility measure chosen is associated with more and/or better travel and activity participation. Conducting this analysis is important to avoid misleading results such as overestimate the impact of policy intervention in social exclusion reduction. The aggregated analysis may also be helpful to identify TRSE cases due to spatial resources issues, such as regions with poor transport systems or lack of activities. However, to have a deep understanding of individuals‘ conversion function limitations, it is necessary to conduct a bottom-up analysis starting from the individual as the unit of analysis.

Finally, most of the TRSE research fails to differentiate between the causal factors behind TRSE and its social outcomes. Many of the TRSE factors are both the cause and result of TRSE. None of the empirical studies reviewed for this chapter set out to establish causal inference between accessibility and level of participation. The vast majority of the papers adopted a correlational research design based on observational data, which is likely to be problematic due to endogeneity issues, such as omitted variables and simultaneity biases. In this sense, more empirical studies that evaluate the causal link between different accessibility measures and activity participation levels are highly desired to develop more successful inclusive transport policies.

Chapter 3

Accessibility Measures for Assessing Transport-Related Social Exclusion: A Critical Review of the Literature

Abstract

The literature on accessibility measures emphasizes the factors shaping accessibility and tends to ignore the relationship between these measures and the goal of accessibility of enabling individuals to participate in the everyday activities of the society in which they are inserted. However, this is a crucial issue since different measures will point to different distributional patterns and suggest different answers about the best policy to reduce social exclusion. In this sense, the choice of accessibility measures should be made carefully and in line with pursued goals. Moreover, the selected measure must be easily operationalised and interpreted; otherwise, practitioners will not use them to inform public policies. In this chapter, we critically reviewed 24 accessibility measures and analysed their theoretical soundness concerning the goal of social inclusion and their practical usability. We developed an analytical framework of 12 criteria, of which ten criteria related to theoretical aspects were derived from the literature about transport-related social exclusion, while the two usability criteria were defined based on the general literature about accessibility measures. The main contribution of this chapter has been to provide a systematic overview of how and to what extent each of the widely used accessibility measures is suitable for assessing transport-related social exclusion. We found three accessibility measures most appropriate to be adopted in inclusive transport policies, cumulative opportunities (CUM), cognitive feasible opportunities

set (CFOS) and number of opportunities within potential path area (NUM). However, the most suitable choice among them will depend on the size of the study area, the type of activity assessed, and the amount of data and computational power available.

3.1 Introduction

From a person's perspective, transport planning aims to provide access options for individuals to the activities they desire, i.e. provide accessibility. When transport does not achieve its goal, individuals can be deprived of access and consequently of participation in activities, becoming at risk of transport-related social exclusion (TRSE) (Luz and Portugal, 2021). There has been a great interest in evaluating transport policies and investments from an accessibility perspective in the last decade (Martens, 2016a). Furthermore, accessibility measures have been valuable tools to assess groups at risk of social exclusion and the benefits and distributional effects of transport policies (Allen and Farber, 2020; Boisjoly and El-Geneidy, 2017a; Curl *et al.*, 2011; Páez *et al.*, 2010).

If the goal to be pursued by transport planning is providing individuals opportunities to access activities, the efforts of accessibility research should be focused on ensuring this is what is measured interventions can be suitably targeted (Curl *et al.*, 2011). Many may wonder why the level of participation in activities is not measured instead of accessibility to assess the risk of social exclusion, given that exclusion occurs when individuals are unable to participate in the everyday activities of a society (Burchardt *et al.*, 1999). Sen (1988) addresses this issue by arguing that people are not necessarily interested in what they achieve but rather in the set of activities they could potentially participate in. Sen (1988) suggests that doing x and choosing to do x are different. According to the example given by Martens (2016b), there is a big difference whether a person visits his grandmother every day because she is the only family member she/he can visit, or whether the same person chooses to visit his grandmother regardless of having the option to visit other family members. The latter person is in a better situation than the former, as he/she has the freedom to choose between several options and can direct his/her life as he/she wishes (Martens, 2016b). Therefore, it would be wrong to assess the situation of both persons only based on their actual level of participation in activities, as this would not take into account the differences in each person's freedoms and abilities to decide the course of their lives (Martens, 2016b).

The importance of accessibility for social inclusion is not in the fact of the individual making use of it by visiting a given place or performing a specific activity, but instead in the range of options of places that the individual can potentially reach Luz and Portugal (2021); Martens (2016b); van Wee (2016). In this sense, accessibility is treated by much of the research on transport-related social exclusion as a key measure for the number of opportunities open to individuals, assuming that higher levels of accessibility are related to more possibilities of participation and greater social inclusion.

The narrative of accessibility provided by the transport-related social exclusion literature suggests that the concept of accessibility is understood as the ability of people to reach and engage in everyday activities in society (Farrington and Farrington, 2005; Farrington, 2007). It means understanding accessibility as a human capability (Luz and Portugal, 2021; Pereira *et al.*, 2017). Based on this perspective, the land use and transport components of accessibility are only resources. The value of these resources will depend on individuals' abilities to convert them into travel and, consequently, access to and participation in activities they value (Hickman *et al.*, 2017; Luz and Portugal, 2021; Vecchio and Martens, 2021). In this sense, the individual's accessibility is represented by the freedom to choose between different options of activities in which they can access and participate.

The appeal of using accessibility notion in inclusive transport policies inevitably implies the need to develop and apply accessibility measures capable of capturing the social inclusion objectives (Boisjoly and El-Geneidy, 2016; Geurs and van Wee, 2004; Handy and Niemeier, 1997; Martens *et al.*, 2012). However, this is not a simple task. The notion of accessibility as a human capability is a more complex and multidimensional concept than those used in transport studies (Luz and Portugal, 2021; Pereira *et al.*, 2017). There are no accessibility measures that can fully capture all the nuances that influence an individual's ability to access and participate in activities. Also, there is no consensus on the best accessibility measures available, nor any agreement regarding definitions and operationalisation of these measures (Handy, 2020; Lei and Church, 2010; Malekzadeh and Chung, 2019).

The literature on accessibility measures emphasises the factors that shape accessibility but tends to ignore the relationship between these measures and the goals of accessibility, such as providing options for activity participation (Martens, 2016b). However, the distributional outcomes of a given transport policy will be considerably influenced by the choice of accessibility measure (Martens and Golub, 2012; Martens *et al.*, 2012; Neutens *et al.*, 2010). Different measures point to different distributional patterns of who are the 'winners' and 'losers' of a given scenario and consequently suggest different answers of what is the best policy to be carried out to increase social inclusion (Martens and Golub, 2012; Miller, 1999; Neutens *et al.*, 2010). In this sense, if the selection of the accessibility measure is made without considering its alignment with the social inclusion objectives, distributional distortions may be expected in the proposed policies (Curl *et al.*, 2011; Geurs and van Wee, 2004; Martens and Golub, 2012; Neutens *et al.*, 2010). Ideally, from a social inclusion perspective, measures should adhere to the goal of ensuring access and participation in activities. Furthermore, the selected accessibility measures must be easily operationalised. Even if the accessibility measure is theoretically consistent, it will not be used in practice if it is not easily operationalised and interpreted by policy-makers (Barboza *et al.*, 2021). he selected accessibility measures should be able to help decision-makers obtain a clear picture of the issue they wish to portray in order to support decision-making (Feitelson, 2002; Martens, 2016b; Morris *et al.*, 1979; Páez *et al.*, 2012).

Papers assessing accessibility measures from a social perspective have already been produced by Martens and Golub (2012), Neutens *et al.* (2010), Geurs and van Wee (2004). However, this chapter differs from the work of Martens and Golub (2012) and Neutens *et al.* (2010) in assessing the theoretical alignment of accessibility measures with the goal of social inclusion. Martens and Golub (2012) and Neutens *et al.* (2010) assess the measures of theoretical soundness according to aspects of equity and justice. Although they overlap in certain aspects, these are different issues. Martens and Golub (2012) explore only theoretical aspects of the measures without assessing how easy is their application in practice. Moreover, they do not assess the accessibility measures individually but instead aggregated by categories. Besides assessing theoretical aspects, this chapter evaluates the usability of each measure individually. While Neutens *et al.* (2010) assessed theoretically and empirically how well accessibility measures articulate equity, this chapter differs from their work by delving into more theoretical issues of the relationship between measures and the social inclusion goals, an aspect not covered by Neutens *et al.* (2010).

Furthermore, this chapter covers a broader range of measures compared to the ten measures analysed by Neutens *et al.* (2010). Geurs and van Wee (2004) work reviews accessibility measures to assess their applicability in transport and land use policy evaluations. Our work differs from theirs by focusing on inclusive transport policy evaluations. Geurs and van Wee (2004) even consider the criterion regarding the possibility of using the accessibility measure as a social measure in their review. However, this is not their paper's focus, and the authors do not delve into this issue. This chapter also differs from Geurs and van Wee (2004)'s work in analysing the measures individually and not by categories. Finally, prior studies about the topic tend to evaluate the theoretical soundness of the measures but neglect the existing trade-off between robustness and usability (Barboza *et al.*, 2021).

In order to fill this gap, this chapter reviews 24 accessibility measures and individually assesses their theoretical adherence to the objective of social inclusion and practical aspects concerning the ease with which these measures can be used and communicated by planners and decision-makers. We develop an analytical framework of 12 criteria, ten of them related to theoretical aspects and two related to the usability of the measures in practice. The criteria related to theoretical aspects were derived from the literature about transport-related social exclusion and transport equity, while the usability criteria were defined based on the general literature on accessibility measures. We identified a small group of measures recommended to assess transport-related social exclusion, cumulative opportunities (CUM), cognitive feasible opportunities set (CFOS) and number of opportunities within potential path area (NUM). However, the most suitable choice will depend on the size of the study area, the type of activity assessed, and the amount of data and computational power available to the planner.

The remainder of the chapter is organized as follows. Section 3.2 establishes the analytical framework to assess accessibility measures. The section 3.3 presents the more prominent accessibility measures available in the literature. Section 3.4 assesses these measures according to the proposed framework. Section 3.5 presents the discussion about which measures are more appropriate for assessing the risk of TRSE. The last section (3.6) is dedicated to the chapter conclusions.

3.2 Analytical Framework

The effectiveness of a transport policy depends on the adherence of the accessibility measure to the policy goals (Boisjoly and El-Geneidy, 2016; Feitelson, 2002; Geurs and van Wee, 2004; Handy and Niemeier, 1997; Martens, 2016b). The practitioner must be aware of the assumptions on which each measure is grounded Guy1983. There is no best approach to measure accessibility for all situations, as different policy goals will require different approaches (Geurs and van Wee, 2004; Handy and Niemeier, 1997; Neutens *et al.*, 2010; Thill and Kim, 2005). Nevertheless, it is possible to derive criteria to assess the usefulness and limitations of accessibility measures according to the purpose of the study (Geurs and van Wee, 2004). If one intends to use an accessibility measure to develop an inclusive transport policy, its theoretical soundness should be determined by its accordance with the goal of social inclusion. Besides being theoretically sound, the selected accessibility measures should be able to help decision-makers obtain a clear picture of the issue they wish to portray in order to support decision-making (Feitelson, 2002; Martens, 2016b; Morris *et al.*, 1979; Páez *et al.*, 2012).

In this section, we establish an analytical framework of 12 criteria to assess the extent to which the previously described accessibility measures articulate the idea of transport-related social exclusion (TRSE) at the theoretical and practical levels. Ten criteria are related to theoretical aspects, while the other two are concerned about the usability and interpretability of the accessibility measures.

3.2.1 Theoretical criteria

The first assessment criterion is whether the measure focuses on the social inclusion objective, which is individual access and participation in activities, and not on other aspects, such as, for example, the ease of movement and the level of service of the infrastructure (Martens and Golub, 2012). Social exclusion occurs when individuals would like to, but for reasons beyond their control, they cannot participate in the everyday activities of the society in which they live (Burchardt *et al.*, 1999). Transport-related social exclusion is the process in which people are prevented from participating in the community's economic, political, and social life because of their reduced accessibility Kenyon *et al.* (2002). The

TRSE defines accessibility as the ability of people to reach and engage in normal activities in a society (Farrington and Farrington, 2005; Farrington, 2007).

Thus, the second criterion is the level of disaggregation, i.e., whether the unit of analysis adopted is the individual or a zone. From a social inclusion perspective, accessibility is a fundamentally individual phenomenon (Miller, 2006) and not always spatially clustered (Hine and Grieco, 2003). In this sense, the focus of accessibility measures should be on people and not places (Martens, 2016a; Preston and Rajé, 2007). Accessibility values aggregated by zones suggest that all individuals in a given zone have the same level of accessibility (Ben-Akiva and Lerman, 1979; Hanson and Schwab, 1987; Neutens *et al.*, 2011; Pirie, 1979), which is not necessarily valid. An accessibility measure to be used as a social measure should ideally describe social and economic opportunities open to the individual (Geurs and van Wee, 2004).

The third criterion is whether the accessibility measure incorporates individuals' perceptions, constraints, and abilities to convert transport and land use resources into access to opportunities. The idea of accessibility from an individual perspective is in line with the notion of accessibility as a human capability (Pereira *et al.*, 2017). Accessibility measures consistent with the capabilities approach should consider individuals' constraints, abilities, and perceptions in converting available resources into opportunities. Farrington (2007, p. 320) states that "a place is not just 'more' or 'less' accessible, but accessible relative to people in all their different circumstances". Accessibility measures that do not articulate individual differences are more likely to generate homogeneous accessibility values and thus suggest equality of opportunity (Neutens *et al.*, 2010). Moreover, measures that do not account for individual aspects tend to overestimate the number of opportunities open to individuals and may suggest that some groups are not at risk of TRSE when, in fact, they are.

A robust accessibility measure should incorporate other elements that influence the ability of individuals to access activities, such as transport resources, land use, and their respective time constraints (Geurs and van Wee, 2004). The fourth criterion is whether the accessibility measure is sensitive to transport changes, i.e., the ease or disutility in terms of distance, time, and monetary cost, an individual faces to travel between an origin and destination (Geurs and van Wee, 2004). The accessibility measure should also be sensitive to changes in the land-use system, i.e., the quantity, quality, and spatial distribution of activities (Geurs and van Wee, 2004). The fifth criterion of the analytical framework is to what extent the accessibility measure incorporates the land use aspects such as quantity, spatial distribution, and competition for activities. Due to time constraints, such as working hours and congestion at rush hours, accessibility to opportunities varies considerably throughout the day (Landau *et al.*, 1981; Neutens *et al.*, 2011). The mismatch between the time constraints imposed by such variations and individuals' commitments can foster social exclusion (Miller, 2006; Neutens *et al.*, 2011). Therefore, the sixth criterion is whether the accessibility measure captures the effects of fluctuations in travel time and availability of opportunities throughout the day with a single calculation or requires multiple "snapshots" in time to articulate this variability (Neutens *et al.*, 2010).

The seventh criterion to be assessed is whether the accessibility measure considers only individual trips or complex chains with multiple trips. The accessibility measure only allows analysing individual trips/activities or considers complex chains with multiple purposes and stops between locations (Handy and Niemeier, 1997; Neutens *et al.*, 2010). Considering the increasing importance of non-home based travel, measures that consider only one reference location (e.g. household) may underestimate the number of opportunities open to individuals (Kwan, 1998; Neutens *et al.*, 2011). Many locations may not be a travel option for an individual departing from their domicile; however, when departing from another closer location (e.g. work), these places become potential destinations (Ben-Akiva and Lerman, 1979; Kwan and Hong, 1998). In other words, accessibility measures that assess accessibility based solely on one reference location, such as the household, ignore the fact that many of the possible trips that contribute to individual accessibility are made from a sequential unfolding of a person's daily activity program (Kwan, 1998)

The eighth criterion of the analytical framework is whether the accessibility measure is based on utility. There are objections to using utility as a parameter for distributive policy interventions (Holtug, 2015; Martens, 2016b; Martens and Golub, 2012; Sen, 2009). Such objections arise from the idea of expensive tastes (as defined by Martens (2016b)) or adaptive preferences (as called by Nussbaum (2001); Ryan and Pereira (2021)), which a person can adjust their expectations according to what she considers social/cultural norms define as normal or acceptable for someone like her (Martens, 2016b;

Martens and Golub, 2012; Nussbaum, 2001; Ryan and Pereira, 2021; Sen, 2009). According to Martens (2016b, p. 20), "the fact that a person has learned to live under harsh conditions, and to smile bravely in the face of it, should not nullify their claim to a better life". In this sense, the use of the satisfaction an individual derives from participation in activities can lead to distorted and counterintuitive results, as the satisfaction obtained may be strongly affected by people's expectations of what is normal, which in turn can be determined by the circumstances to which the person has become accustomed to (Martens, 2016b; Ryan and Pereira, 2021). This phenomenon is known as expensive tastes or adaptive preferences (Martens and Golub, 2012; Nussbaum, 2001; Ryan and Pereira, 2021). The use of utility /welfare as a distributive parameter may shift the focus of policies towards people with high expectations of activity participation and transport system performance, rather than people who have learned to accept a relatively poor transport system and the limitations imposed on the range of opportunities they can engage in (Martens, 2016b). From a distributional perspective, using welfare/utility as a distributive parameter would suggest that we need to provide more transport and land use resources to people with high expectations than to those with low expectations to ensure equality of welfare.

The ninth criterion of the analytical framework is whether the accessibility measure is grounded on the individual's observed travel behaviour or is based on the range of activities that the individual can potentially achieve. Is the measure based on assumptions regarding people's actual travel behaviour, which Páez *et al.* (2012) termed as a positivist approach, or does it represent what people can potentially achieve without replicating biases in past travel behaviour patterns? People are interested not only in the actual state they achieve but also in the range of states (activities) they could achieve (Luz and Portugal, 2021; Martens, 2016a; van Wee, 2016; van Wee and Geurs, 2011).Sen (1988) gives the example of fasting. It is an entirely different situation if a person has the opportunity to eat and decide not to than a situation in which a person does not to eat because he or she does not have access to food. The value of the option chosen depends not only on the characteristics of that option but also on the range of options available to the individual (Luz and Portugal, 2021; Martens, 2016a; van Wee, 2016). From a social inclusion point of view, the accessibility measure must measure the possibilities of activity participation and not replicate behavioural biases (Martens and Golub, 2012).

The tenth criterion is whether the accessibility measure assumes an optimization/maximization strategy. In other words, accessibility measures that indicate only the most advantageous opportunity for the individual, for example, the closest opportunity or the one that provides the greatest utility. Accessibility measures that adopt a maximization or optimization strategy are not suitable to assess the TRSE risk (Martens and Golub, 2012). Based on the argument that individuals value the range of options available to them, the adoption of maximization rules is restrictive and leaves little room for other decision rules that individuals may adopt when selecting activities to participate in (Neutens *et al.*, 2010).

3.2.2 Usability and Interpretability criteria

The analytical framework eleventh criterion is the ease with the accessibility measure is applied in practice in terms of the availability of data, models, and techniques, ease of access to data by transport authorities, and time and budget for its computation (Geurs and van Wee, 2004; Malekzadeh and Chung, 2019). Researchers have developed various accessibility measures with different data requirements and complexity. These measures are increasingly detailed due to the growing data availability and advances in computing power (Barboza *et al.*, 2021). Nevertheless, one of the main challenges faced by accessibility planning is obtaining high-resolution data (Malekzadeh and Chung, 2019). The operationalisation of accessibility measures requires a wide range of data which, in general, has severely restricted access globally (Malekzadeh and Chung, 2019), particularly in Global South countries. Besides the data restriction, limitations exist in calculating the accessibility measures due to poorly trained technical staff and the low processing power of the equipment available at the transport planning agencies in Global South regions. In this sense, planners and policymakers, or even researchers in these regions, continue to opt for simple, practical and straightforward measures to guide them in policymaking, despite a large number of accessibility measures available (Barboza *et al.*, 2021; Bertolini *et al.*, 2005; Kelobonye *et al.*, 2020).

The last criterion is the extent to which policymakers and researchers can easily communicate and interpret the accessibility measure. The selection of accessibility measures cannot be solely based on theoretical soundness. Aspects such as ease of operationalisation and interpretability/communicability are equally important (Barboza *et al.*, 2021; Geurs and van Wee, 2004). Even if measures are highly theoretically consistent, policymakers will not use them in the planning process if they are not easy to operationalise and interpret (Barboza *et al.*, 2021; Koenig, 1980; Malekzadeh and Chung, 2019). Simple measures that require few or readily available data are preferable to more complex and data-intensive measures. According to Feitelson (2002), measures are tools to communicate important information about a given issue in a simplified way to policymakers and the general public. Therefore a good accessibility measure is intuitive, easily interpretable, and communicable to researchers, decision-makers, and the general public (Boisjoly and El-Geneidy, 2016; Geurs and van Wee, 2004; Páez *et al.*, 2012). As important as the measure's theoretical foundation and ease of operationalisation is its interpretability/communicability. If the selected measures cannot convey a clear "picture" of the situation to policymakers, they are unlikely to be used in the planning process.

The 12 criteria established for the analytical framework are as follows:

- **Criterion 1**: Does the measure focus on access to activities?
- **Criterion 2**: What is the unit of analysis used by the measure?
- **Criterion 3**: Does the measure incorporate the individual's constraints, abilities, and perceptions?
- **Criterion 4**: How sensitive is the measure to the ease or disutility (distance, time, and monetary cost) an individual faces in moving between an origin and a destination?
- **Criterion 5**: How sensitive is the accessibility measure to land use aspects, such as quality, quantity, and spatial distribution of activities?
- **Criterion 6**: Does the accessibility measure capture the effects of fluctuations in travel time and availability of opportunities throughout the day with a single calculation?
- **Criterion 7**: Does the measure account only for single trips/activities or consider complex chains of multiple trips/activities between origins and destinations?

- **Criterion 8**: Does the measure use the utility as a parameter for calculating the accessibility score?
- **Criterion 9**: Is the measure derived from observed travel behaviour and carried out activities, or does it assess what people can potentially achieve without replicating biases of past travel behaviour patterns?
- **Criterion 10**: Does the measure assume a maximization strategy in the choice process?
- **Criterion 11**: How easily is the measure operationalised regarding data, models and techniques, time, and budget availability?
- **Criterion 12**: How easily policymakers and researchers can communicate and interpret the measure?

3.3 Accessibility Measures

Accessibility has been widely used in the transport field and studied by various disciplines, such as geography, transport engineering, urban planning, and economics. Despite the popularity of the accessibility concept, there is no consensus regarding its meaning, and various definitions are found in the literature (Handy, 2020; Lei and Church, 2010; Malekzadeh and Chung, 2019).Hansen (1959, p. 53) first defined accessibility as the "potential of opportunities for interaction". Over time, several other conceptualisations have emerged, such as:

- "The ability of a transportation system to provide a low cost and/or quick method of overcoming the distance between different locations" (Ingram, 1971, p. 101);
- "accessibility indicates the inherent characteristic (or advantage) of a place with respect to overcoming some form of spatially operating source of friction" (Dalvi and Martin, 1976, p. 18);
- "A measure of spatial separation of human activities. Essentially it denotes the ease with which activities may be reached from a given location using a particular transportation system" (Morris *et al.*, 1979, p. 91);

- “ease and cost of point-to-point movement” (Wachs and Kumagai, 1973, p. 441);
- the freedom of individuals to decide whether or not to participate in different activities (Burns, 1979);
- “the ease of travel between zones in the urban area solely in terms of the characteristics of the existing transport system” (Leake and Huzayyin, 1980, p. 11);
- “accessibility is related to choice contexts for spatial interaction, referring to a spatial actor with given personal attitudes and resources who acts from one or several fixed geographical locations” (Weibull, 1980, p.54);
- the benefits provided by a transportation/land use system (Ben-Akiva and Lerman, 1985);
- "the extent to which land use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)" (Geurs and van Wee, 2004, p. 128);
- “ the ability of people to reach and take part in activities normal for that society (Farrington, 2007, p. 320); and
- “the amount and the diversity of places of activity that can be reached within a given travel time and/or cost” (Bertolini *et al.*, 2008, p. 209).

According to the field of study, the accessibility definition may assume a different focus, such as proximity, ease of spatial interaction, the potential of opportunities for interaction, freedom of choice, and benefits obtained by the individual of land use and transport resources. Due to the variability of approaches, accessibility has been measured in different ways according to the study’s objective.

Several literature reviews about accessibility measures were published before. Morris *et al.* (1979) reviewed what they called perceptual and measurable specifications of accessibility measures, grouping them by conceptual basis and establishing their relevance to transport planning. Pirie (1979) examined the limitations, strengths and the theoretical basis of five different accessibility measures. Koenig (1980), in turn, focused on the difference between the existing theoretical basis of accessibility, with emphasis on the utility approach. Handy and Niemeier (1997) devoted efforts to translate theoretical concepts into operational measures of accessibility, providing a conceptual framework to facilitate practical applications. Handy and Niemeier (1997) framework covered three aspects of accessibility measures: specification, calibration and interpretation. Kwan (1998) compared eighteen place-based and people-based accessibility measures, including their computational and data requirements and the degree of correlation between them.

Geurs and van Wee (2004) adopted a comprehensive framework for assessing accessibility measures based on four aspects: theoretical basis, operationalisation, interpretability and communicability and usability. Geurs and van Wee (2004) identified the four components that influence accessibility: transport system, land use system, temporal and individual, and proposed a comprehensive classification of accessibility measures into categories: infrastructure-based, place-based, utility-based and people-based. Talen and Anselin (1998) compared four place-based accessibility measures to highlight the equity impacts in urban public services access due to the chosen measure. Neutens *et al.* (2010) further developed Talen and Anselin (1998)'s work and assessed the implications for assessing equity of urban service distribution according to the choice of accessibility measure. They found substantial differences between people-based and place-based measures. According to different philosophical theories, Martens and Golub (2012) qualitatively explored the types of accessibility measures to be used in the equity analysis of transport policies. Kwan (1999), in turn, reviewed place-based and people-based accessibility measures and applied three different people-based measures to demonstrate gender inequality of access. Lei and Church (2010) and Malekzadeh and Chung (2019) focused their reviews on measures of public transport accessibility, highlighting their advantages and shortcomings.

Based on several review papers and additional empirical works about accessibility, this section characterizes the most prominent measures found in the literature. The measures are categorised in three categories: place-based, utility-based and spatio-temporal measures. To not dwell on describing all accessibility measures found in the literature, we do not discuss some accessibility measures considered less adherent to the definition of accessibility from a social inclusion perspective. Among the discarded measures are infrastructure-based measures such as congestion level, average travel speed, headway of services, PTAL (Public Transport Accessibility Level) (Wu and Hine, 2003) and more complex measures that analyse a node's relative performance or area in the transport network using graph theory (Owen and Levinson, 2015).

Given the many accessibility measures to be presented, we describe in Table 3.1 the correspondence of each acronym adopted to refer to the accessibility measure. In addition, we have tried to unify the mathematical notation used in all measures. Figure 3.1 presents the accessibility measures found in the literature and their respective category. Table 3.2 presents the general notation of the accessibility components.

Table 3.1: Glossary for the abbreviated names of the measures

Acronym	**Name**	**Sub-category**	**Category**
$DMIN$	Minimum Distance	Distance or time-based	Place-based measures
$TMIN$	Minimum Time		
$DMIN_{Trans}$	Minimum Distance to Public Transport Stop		
$TMIN_{Trans}$	Minimum Time to Public Transport Stop		
$DCBD$	Distance to CBD		
BT	Balancing-Time	Balancing-Time measure	
$PTPR$	Population-to-Provider Ratio	Container and	
$CONT$	Container	Population-to-Provider Ratio	
$GRAV$	Gravity-Type	Gravity-based	
$GRAV_{Comp}$	Gravity Accounting for Competition		
CUM	Cumulative Opportunities	Cumulative Opportunities	
CUM_{Comp}	Cumulative Opportunities Accounting for Competition		
$UTIL$	Utility-based	Utility-based	Utility-based measures
$VSTP$	Space-time prism Volume	Lenntorp	Spatio-Temporal
$APPA$	Area of the Potential Path Area		measures
LEN	Length of Network Arcs		
NUM	Number of Opportunities		
$CFOS$	Cognitive Feasible Opportunity Set		
$NUMD$	Proximity of Opportunities in Daily Potential Path Area	Hybrids of Lenntorp and	
WA	Weighted Sum of the Opportunities	Burns-Miller	
DUR	Possible Activity Duration of Opportunities in Daily Potential Path Area		
$BAGG$	Aggregated Utility of Opportunities in Daily Potential Path Area	Burns-Miller	
$BMAX$	Maximum Utility of Opportunities in Daily Potential Path Area		
$BTTRANS$	Expected Maximum Utility of Opportunities in Daily Potential Path Area		

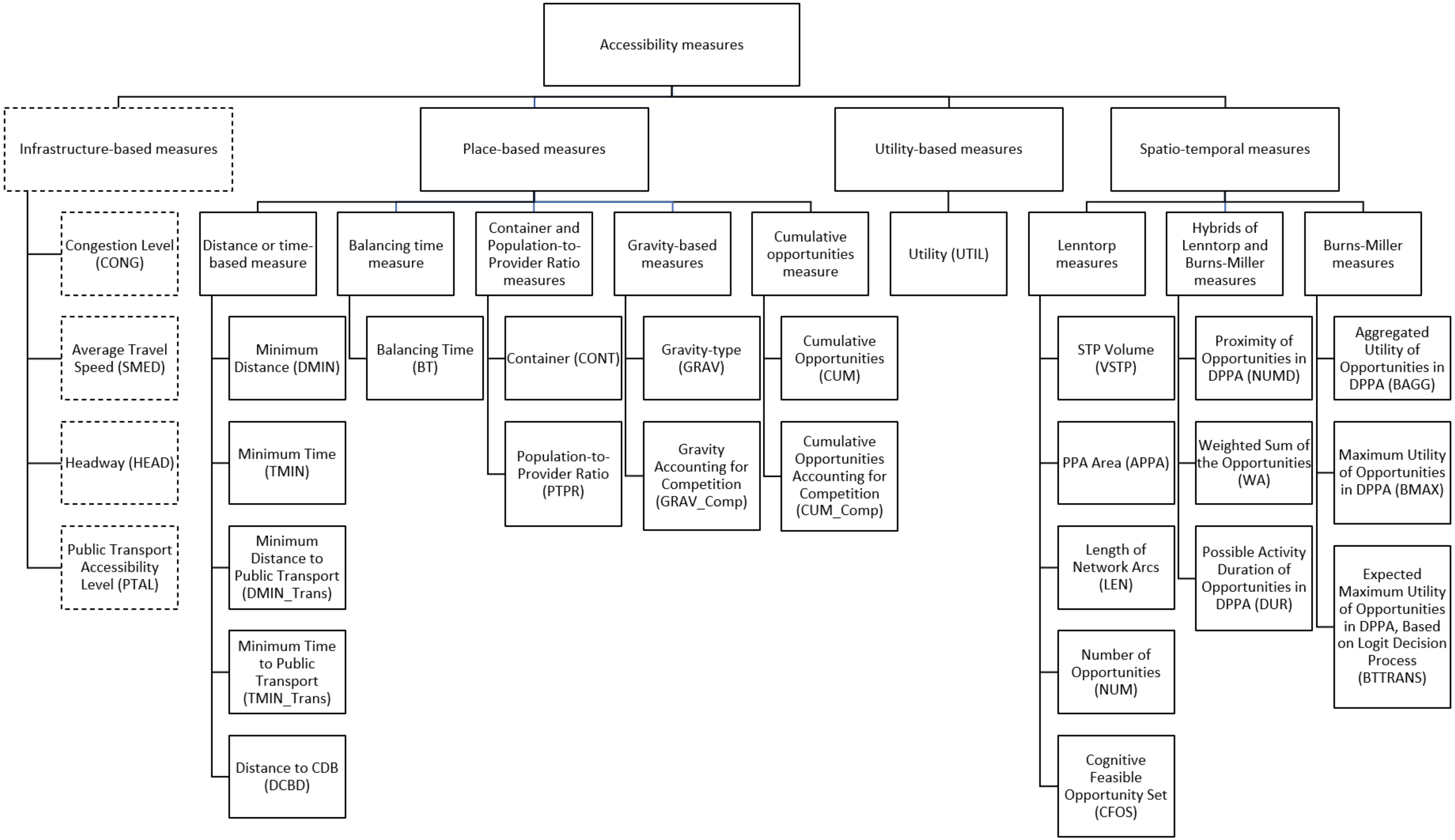


Figure 3.1: Accessibility measures organised by categories.

Source: Author's elaboration

Table 3.2: General notation of the accessibility components

Place-based accessibility measures variables	
d_{ij}	Distance between reference location I (origin) and destination j
t_{ij}	Travel time between reference location I (origin) and destination j
p_i	Population of zone i
O_j	Number of opportunities in zone j
$O_{k,}$	Number of opportunities of type k
${C_{ij}}^v$	Generalized cost of transport from i to j using transport mode v
$f\left(C_{ij}\right)$	Deterrence function for the travel cost (time, distance, or monetary) between origin i and destination j
a_j	Attractiveness of opportunities in the area j
P_i^v	Number of people in zone i who travel using mode v to seek opportunities
δ	Generalized travel cost threshold
Utility-based accessibility measure variables	
U_{is}	Utility that individual i obtains from alternative s
V_{is}	Non-random portion of the utility that individual i obtains from alternative s
ε_{is}	Random portion of the utility that individual i obtains from alternative s
Spatio-temporal accessibility measures variables	
p_i	Anchor location of mandatory activity at time i
$t_{i+1} - t_i$	Available time to participate in a discretionary activity between mandatory activities i and $i+1$
t_{i+1}	Latest possible arrival time at the mandatory activity p_{i+1}.
t	Time at which the discretionary activity takes place
$t_{p_i q}$	Travel time from the anchor location p_i to the location q of the discretionary activity
$t_{qp_{i+1}}$	Travel time from the location q of the discretionary activity to the next anchor location of the mandatory activity p_{i+1}
$\overline{T}$	Minimum duration of the discretionary activity
t_q^o	Opening hour of the activity q
t_q^c	Closing hour of the activity q
l	Arc of the transport network
L_l	Length of the l arc of the transport network
$R(l)$ and $R(q)$	Function that assumes value one if the arc l or discretionary activity q is within the DPPA.
λ_m	Parameter of the distance decay function for the transport mode m.
t_q^e	The earliest possible start time for discretionary activity q
t_q^s	The latest possible end time for discretionary activity q

3.3.1 Place-based measures

Measures based on distance or time

Place-based measures of accessibility can be integral and relative (Ingram, 1971). Relative accessibility is "the degree to which two places (or points) on the same surface are connected" (Ingram, 1971, p.101). The integral accessibility of a given point is "the degree of interconnection with all other points on the same surface" (Ingram, 1971, p.102) and derives from the sum of the relative accessibilities of this point. Morris *et al.* (1979) state that integral accessibility is a measure of total travel opportunities, while relative accessibility is the effort involved in making a trip.

From the concept of relative accessibility, the most straightforward measures of accessibility, such as minimum distance ($DMIN$) and minimum time ($TMIN$), can be derived (Geurs and van Wee, 2004). Such measures are called separation measures (Morris *et al.*, 1979; Pirie, 1979) and are often used in land use planning as the maximum travel distance or time to a particular location or transport infrastructure (Geurs and van Wee, 2004; Lei and Church, 2010). $DMIN$ and $TMIN$, respectively, denote the distance in the transport network and the travel time between an individual's reference location and the nearest opportunity assessed (Talen and Anselin, 1998). If a person lives further away from an opportunity, his or her individual accessibility is assumed to be lower (Guy, 1983; Neutens *et al.*, 2010).

Mathematically, the minimum distance measure or minimum time can be defined as follows:

$$DMIN_i = \min |d_{ij}| \tag{3.1}$$

$$TMIN_i = \min |t_{ij}| \tag{3.2}$$

When the destination is a public transport stop (j=public transport stop) , accessibility measures become ($DMIN_{Transi}$ and $TMIN_{Transi}$). Like the minimum distance accessibility measures, Song (1996) proposed the accessibility measure denoted by the distance to CDB ($DCBD$). A location has better accessibility if it is closer to the CBD.

Balancing time measure

The balancing time (BT) measure refers to the required travel time (t_i) using public transport to access a number of jobs equal to the economically active population (p_i) of the origin zone (i) (Barboza *et al.*, 2021). BT is defined as follows:

$$Minimise\ t_i, \tag{3.3}$$

subject to:

$$\sum_{j=1}^{n} O_j f\left(t_{ij}\right) \geq p_i \tag{3.4}$$

$$f\left(t_{ij}\right)=\begin{cases}1, \ se\ t_{ij}\leq t_i\\ 0, \ se\ t_{ij}>t_i\end{cases} \tag{3.5}$$

The BT measure can also be generalized to other activities with limited supply (ex: school vacancies and hospital beds). Also, BT can be disaggregated according to the job complexity and the population's level of education or medical needs. One of the BT critical issues is its high sensitivity to the spatial unit area.

Container and Population-to-Provider Ratio measures

Container type accessibility measures ($CONT$) also known as floating catchment area, denotes the number of facilities or services contained within a given spatial unit (for example, census tract) (Talen and Anselin, 1998). The population-to-provider ratio ($PTPR$) denotes the ratio of $CONT$ by the spatial unit population Neutens2015a. $PTPR$ is commonly used to measure accessibility to employment or other activity with limited supply (e.g., school vacancies, hospital beds), where the number of job places (or other activity) is divided by the number of workers (or other groups of individuals) within the area (Shen, 1998).

Formally, the $CONT$ measure is defined as:

$$CONT_i=\sum_k O_k, \ \forall k \tag{3.6}$$

Where O_k is the number of facilities or services (j) within spatial unit i. Population-to-provider ratio ($PTPR$) measure, in turn, is the ratio between $CONT$ and the population of the spatial unit (p_i).

$$PTPR_i=\frac{\sum_k O_k}{p_i}, \ \forall k \tag{3.7}$$

According to Neutens Neutens (2015), these two types of measures have been widely used by researchers in the field of public health, mainly for their ease of implementation and low requirement of knowledge of GIS software. One of the problems that these measures suffer from is the definition of the contour area. Usually, artificial zoning (census sector, neighbourhood) is used depending on the data availability (Neutens, 2015).

Gravity-based measure

The gravity-based accessibility measures ($GRAV$) , also called potential or attraction measure, was first introduced by Hansen (1959) and is one of the most famous types of place-based accessibility measures, having been widely used in urban and geography studies (Geurs and van Wee, 2004; Horner and Downs, 2014). Gravity-type measures are derived from the travel distribution model (Handy and Niemeier, 1997) and make an analogy with physics' Law of Universal Gravitation (Weibull, 1976).

$GRAV$ derives from a spatial interaction framework in which weights are assigned to opportunities via an attractiveness factor and discounted by a separation cost from the reference point (Dong *et al.*, 2006; Kwan, 1998; Malekzadeh and Chung, 2019; Miller, 1999; Neutens *et al.*, 2010). Such separation costs are expressed by an impedance function specific to the transport mode used (Neutens *et al.*, 2010). The accessibility at point A to a particular type of activity in area B will be directly proportional to the attractiveness of the activity in area B and inversely proportional to a function of the generalized cost of travel from point A to area B (Hansen, 1959; Koenig, 1980). Mathematically, the general formula of the gravitational accessibility measure ($GRAV$) is:

$$GRAV_i = \sum_j a_j f\left(C_{ij}\right) \tag{3.8}$$

where, a_j is the attractiveness of opportunities in the area j; C_{ij} is the generalized cost of transport from i to j; and $f\left(C_{ij}\right)$ is the deterrence function.

$GRAV$ measures can vary according to the generalized cost unit adopted, the period of the day when it is measured, the transport mode, the attractiveness factor, the impedance function, and the level of disaggregation (Morris *et al.*, 1979). Attractiveness factor can be a count of the number of opportunities, the total area of retail establishments, the number of households, the number of jobs, etc., depending on the purpose of the analysis (Kwan, 1998). The generalized transport cost unit is also flexible. Different elements may be considered, including travel time, distance, monetary cost, or a combination of those (Levinson and Wu, 2020; Morris *et al.*, 1979). Bocarejo S. and Oviedo H. (2012), for example, combined travel time and monetary cost using an exponential deterrence function to calculate accessibility to jobs in Bogotá, Colombia. Miller (2018) suggests that travel time is generally a better measure of user-perceived impedance than distance. However, it is worth noting that in developing countries, the monetary cost associated with making the trip may be a stronger impedance than travel time (Herszenhut *et al.*, 2021; Lucas, 2011).

Most discussions about gravity-based accessibility measures revolve around the best deterrence function (Geertman and Ritsema Van Eck, 1995). The most common functions are negative exponential, Gaussian, inverse, log-normal, log-logistic, gravitational, potential, rectangular, square root exponential, negative power, and linear (Levinson and Wu, 2020). According to Páez *et al.* (2010), continuous impedance functions (e.g., potential and negative exponential) tend to generate maps with more general patterns because of the smoother variation between zones. Despite the wide variety of deterrence functions, the negative exponential remains the most widely used as it is more adherent to the travel behaviour theory (Geurs and van Wee, 2004; Handy and Niemeier, 1997; Kwan, 1998; Shen, 1998; Thill and Kim, 2005). In addition to the difficulties associated with choosing the best impedance function, it is also hard to define the friction parameter of the function. Generally, the calibration of this parameter is case-specific, and it is usually based on travel behaviour (Geertman and Ritsema Van Eck, 1995; Kwan, 1998). This issue raises concerns regarding the transferability of the parameters to other areas of study (Páez and Farber, 2012).

Besides the issues associated with the impedance function choice, there is difficulty in defining the friction parameter of the function (when the function requires such a parameter). Generally, the calibration of this parameter is context-specific, usually based on travel behaviour (Geertman and Ritsema Van Eck, 1995; Kwan, 1998), which may raise concerns regarding the transferability of these parameters to other study areas Paez2012c. According to Neutens (2015), applications of gravity measures in studies on access to health facilities usually use constant arbitrary impedance parameters for a priori defined bandwidths of travel distance. Also according to Neutens (2015), this is partly because negative exponential decay parameters cannot be reliably estimated without detailed information on the evolution of the utilization rates of health facilities as a function of distance. Weibull (1976) developed a mathematical formalisation to develop gravity-type measures into six axioms. Miller (1999) translated the mathematical formulation of the axioms as follows:

1. The order in which opportunities are presented in a set of activities should not affect the accessibility value.
2. The accessibility value should be nonincreasing in distance and nondecreasing in activity attraction
3. The accessibility of an opportunity at zero distance should be continuous and increasing.
4. A single opportunity with infinite attraction located at zero distance should be better than any pair of opportunities with finite attractions.
5. Opportunities with zero attraction should not contribute to the value of the accessibility measure.
6. If two sets of opportunities are equivalently accessible, then adding the same new opportunity to both sets should not change this equivalence

Variations of gravity-based accessibility measures are also found in the literature to assess the effects of competition for jobs or vacancies of a particular opportunity. According to Shen (1998), studies that examine the spatial characteristics of urban unemployment consider only the supply side of the accessibility measure, and the demand side - the competition for available opportunities - are not accounted for (Morris *et al.*, 1979; Shen, 1998). However, the number of relevant employment opportunities available in a given area will also depend on the number of people competing for these opportunities (Morris *et al.*, 1979). Weibull (1976) theoretically explored this issue, and Shen (1998) developed a modified gravity-based measure to incorporate the demand side. The gravity-based measure that accounts for competition ($GRAV_{Comp}$) proposed by Shen (1998) is mathematically defined as follows:

$$GRAV_{Comp_i} = \sum_v \left[\left(\frac{P_i^v}{p_i} \right) \bullet \left(\sum_j \frac{O_j \bullet f\left(C_{ij}^v\right)}{\sum_m \sum_k P_k^m \bullet f\left(C_{kj}^m\right)} \right) \right] \tag{3.9}$$

Where $P_i^v is$ the number of people in zone i who travel using mode v to seek opportunities; p_i is the total number of people in zone i; P_k^m is the number of people living in zone k who travel using mode m to seek opportunities; $f\left(C_{ij}^v\right)$ e $f\left(C_{kj}^m\right)$ are impedance functions for mode v and m, respectively; for a transport system with M modes, v, $m = 1, 2, \ldots, M$; and O_j is the number of opportunities in zone j.

Cumulative opportunities measure

The cumulative opportunities measure (CUM), also called isochronic or contour measure, is one of the most popular measures of accessibility, widely used in urban planning and geography studies (Geurs and van Wee, 2004). The CUM measure was first introduced by Wachs and Kumagai (1973, p.441), who defined it as "the number or density of travel opportunities of particular types within certain time distances or travel-cost ranges from the residential locations of populations group of interest". Currently, CUM assesses the number or proportion of activities that can be reached within a given travel time, distance or monetary cost from the reference location (Geurs and van Wee, 2004; Handy and Niemeier, 1997; Hanson and Schwab, 1987; Herszenhut *et al.*, 2021; Koenig, 1980; Kwan, 1998; Talen and Anselin, 1998). El-Geneidy *et al.* (2016) calculated the CUM based exclusively on travel time, solely on public transport fare, and with a combination of both. They found that not incorporating monetary costs into the generalized cost of travel tends to overestimate accessibility values. Despite this finding, few studies incorporate the monetary cost as a travel impedance in accessibility analyses (Herszenhut *et al.*, 2021; Malekzadeh and Chung, 2019).

The equation for the CUM measure is defined as follows:

$$CUM_i = \sum_j O_j \bullet f\left(C_{ij}\right), \qquad \delta > 0, \tag{3.10}$$

Where a_j is the number of opportunities in j, δ is a generalized travel cost (time, distance or monetary) threshold, C_{ij} the travel cost between location i and location j, and

$e\ f\ (C_{ij})$, assumes the value one if $C_{ij} \leq\ \delta$ and 0 if $C_{ij} > \delta$. Some authors consider CUM as a particular case of the gravitational accessibility measure, with the attraction measure equal to the number of opportunities and a rectangular impedance function, i.e., equal to 1 if the travel time is less than the defined threshold, or 0 otherwise (Dong *et al.*, 2006; Koenig, 1980).

Unlike the classic gravity-based measure, CUM weights all opportunities equally, with more distant opportunities receiving equal weights to closer opportunities. Such a characteristic emphasizes the number of destinations or potential opportunities rather than their proximity (Handy and Niemeier, 1997). Due to this feature, accessibility value increases progressively as the travel cost threshold increases (Ben-Akiva and Lerman, 1979; Kwan, 1998; Pirie, 1979).Black and Conroy (1977) developed a slightly different cumulative opportunity measure that consists of the area under the cumulative distribution curve of opportunities achieved within a travel time threshold to address this issue.

Inspired by Shen (1998)'s gravity-based measure that accounts for competition, Kelobonye *et al.* (2020) developed a cumulative opportunity measure that considers the supply side and the demand for opportunities. The formula of the cumulative opportunity measure that accounts for competition (CUM_{Comp}) proposed by Kelobonye *et al.* (2020) is:

$$CUM_{COMP_i} = \sum_{j=1}^{n} \frac{O_j \bullet f\,(C_{ij})}{\sum_{k=1}^{n} P_k \bullet f\,(C_{kj})} \tag{3.11}$$

$$f\,(C_{ij}) = \begin{cases} 1, \text{ for } t_{ij} \leq\ \delta. \\ 0,\ otherwise \end{cases} \tag{3.12}$$

$$f\,(C_{kj}) = \begin{cases} 1, \text{ for } t_{kj} \leq\ \delta. \\ 0,\ otherwise \end{cases} \tag{3.13}$$

Where O_j denotes the opportunities in zone j, P_k is the competing demand for opportunities in zone k, $f\,(c_{ij})$ and $f(c_{kj})$ are deterrence functions of the travel time and δ the travel cost threshold.

Biases in place-based measures

Levinson and King (2020) point out that at least five biases may arise in spatial statistical analysis conducted using place-based accessibility computations: edge effects, modifiable areal unit problem (MAUP), modifiable temporal unit problem (MTUP), and starting point-related effects.

Edge effects are a bias in spatial analysis resulting from the imposition of an explicit, discrete boundary (e.g., the boundary of the cumulative opportunity measure or the container measure) on continuous spatial phenomena in space (Levinson and King, 2020). It may occur when transport networks and regions are cut off outside the study area and therefore not represented and counted. Levinson and King (2020) suggest defining the study areas based on functional urban areas, regardless of administrative boundaries, to overcome the problem.

Place-based measures are generally zonal. It means that what is measured is the accessibility that groups of individuals supposedly congregated at zone centroids have to opportunities clustered likewise (Pirie, 1979). Therefore, a crucial issue of place-based measures is the level of spatial disaggregation (Handy and Niemeier, 1997; Pirie, 1979). Smaller zones tend to provide more accurate accessibility results for individuals in that area (Handy and Niemeier, 1997). Some authors have also introduced non-zonal measures of accessibility, i.e., using a point-based spatial unit (Guy, 1983; Hanson and Schwab, 1987; Kwan, 1998). In this approach, the unit of analysis is the individual, and all locations are represented as distinct points in space (Kwan, 1998; Neutens *et al.*, 2011).

The possibilities of zoning definition are almost infinite, resulting in a modifiable areal unit problem (MAUP). MAUP refers to the bias related to spatial data aggregation resulting when two identical analyses are applied using different spatial scales or zoning schemes (Dalvi and Martin, 1976; Kwan, 1998; Levinson and King, 2020; Neutens, 2015). MAUP can generate two problems: scale and zone effects (Dalvi and Martin, 1976; Levinson and King, 2020). The scale effect refers to how the same spatial data will yield different results when aggregated using differently scaled geographies (Levinson and King, 2020). The zoning effect refers to how the same spatial data, when aggregated using similarly scaled geographies, but different zone shapes can yield very different results.

For example, aggregation using square grids will produce different results than using a hexagonal grid (Levine, 2020). MAUP biases can be minimized using spatial units whose boundaries have the same distance from the centre of the shape regardless of where along the boundary the measurement is taken, and by using small-sized spatial zones to reduce the bias from discrete discontinuities between origins and destinations (Levinson and King, 2020; Páez and Scott, 2004).

In addition to spatial disaggregation, it is possible to increase the sophistication of place-based measures by segmenting them by different trip purposes, modes of transport, travel times, and socio-economic characteristics (Handy and Niemeier, 1997; Pirie, 1979). According to Pirie (1979), stratification can also be done by including the perception of individuals, such as replacing the objective measurement of time or distance with a subjective (perceived) value. By requiring a larger amount of data, disaggregation has practical limits and is likely to present diminishing returns in terms of accuracy (Handy, 1993). In this sense, Pirie (Pirie, 1979) suggests that planners should clearly understand the pursued objectives of the accessibility assessment to define a suitable level of disaggregation.

Travel times vary throughout the day due to congestion and aspects related to transport service provisions, such as route, timetable, and modal shift synchronization (Farber *et al.*, 2014; Miller, 2018). In this regard, Farber *et al.* (2014) argue that accessibility provided by public transport is inherently dynamic and that static measures of accessibility, i.e., those measured at only one period of the day, may not adequately represent actual accessibility levels. The authors assessed accessibility temporal variability to supermarkets in Cincinnati, Ohio (USA) by calculating and analysing travel times by public transport at all minutes of the day. The results showed significant variability in accessibility levels throughout the day. Owen and Levinson (2015) also studied accessibility temporal variability by calculating it for every minute in the morning peak hour (between 7 am and 9 am), which they termed “continuous accessibility”. The study conducted in the Minneapolis-Saint Paul, Minnesota (USA) metropolitan area showed that accessibility levels increase as departure times at nearby stops approach and drop after departing trips. Furthermore, the accessibility profile analysis showed deep troughs at times with few or no upcoming trip departures at nearby stops, while sustained periods of high accessibility are associated with periods with frequent departures.

Farber *et al.* (2014) and Owen and Levinson (2015) faced the modifiable temporal unit problem (MTUP). MTUP is the third type of bias found in place-based accessibility measures and refers to how the results of an analysis may vary depending on how the data are organised using different temporal schemes (Levinson and King, 2020; Pereira, 2019). Pereira (2019) identifies three effects of MTUP: aggregation effects, boundary effects and segmentation effects. The aggregation effect suggests that aggregating data in a temporal window using different windows and sample sizes will produce different results. For example, the results will vary when calculating average accessibility from different departure times depending on the number of departures and the time interval considered (Levinson and King, 2020; Pereira, 2019). The segmentation effect relates to the selection of starting point of that time window (Pereira, 2019).The boundary effect, in the case of MTUP, suggests that considering different time boundaries may produce different results. For example, the calculation of the cumulative opportunity measure will vary considerably according to the time threshold set(Levinson and King, 2020; Pereira, 2019).

Levinson and King (2020) provide recommendations to circumvent MTUP. The first is to analyze accessibility levels throughout the day to capture variations in the level of service during peak and off-peak times and differences in opportunities by the time of day. The second is to use multiple start times, considering trade-offs between computational costs and the reliability of results. The third would be to conduct sensitivity analyses with multiple time thresholds when using cumulative opportunity measures. According to Levinson and King (2020), this strategy can generate more robust results, guaranteeing conclusions that are not only resulting from ad hoc methodological choices.

Although Farber *et al.* (2014) and Owen and Levinson (2015) identified the problem of MTUP in their work, Boisjoly and El-Geneidy (2016), on the other hand, found that measuring job accessibility at 8 am is a valid approximation of relative accessibility throughout the day in the Greater Toronto Area (Canada). Thus, the lack of a consensus on the temporal variation in accessibility levels indicates that this issue requires further study.

Levinson and King (2020) pointed out that the fifth type of bias is the starting point bias. This type of bias refers to small changes in the starting point that can create non-linear changes in cumulative travel times or other statistics. According to Levinson and King (2020), minimizing starting point effects requires identifying representative starting or arrival points for analysis or using a sample with many different starting and arrival points. An alternative to overcome the issue is to use disaggregated and compact spatial units for both destinations and origins. When it is not possible, Levinson and King (2020) suggest creating representative centroids for the zones through measures of centrality or averages weighted towards population concentration within the zones.

3.3.2 Utility-based measures

Utility-based measures are grounded in the economic theory of consumer surplus and random utility (Ben-Akiva and Lerman, 1985; Burns and Golob, 1976; de Jong *et al.*, 2007; Dong *et al.*, 2006; Handy and Niemeier, 1997; Niemeier, 1997). The boundary between these two approaches applied to accessibility is blurred and often leads to the same results depending on the assumptions adopted (Morris *et al.*, 1979). The rationality behind utility-based accessibility measures is that individuals as rational beings make choices that maximize their utility, i.e., maximize their benefit derived from access activities (Ben-Akiva and Lerman, 1985; Geurs and van Wee, 2004; Lei and Church, 2010; Levinson and Wu, 2020; Neutens *et al.*, 2011). The utility-based measures calculate the maximum net utility - represented by the utility obtained from the spatial interaction between the transport system and land use deducted by the cost of travel - obtained from a single opportunity compared to a range of available options (Burns and Golob, 1976; Geurs and van Wee, 2004; Handy and Niemeier, 1997; Koenig, 1980; Levinson and Wu, 2020). Measures in this category compute the accessibility at the individual (or group of individuals) level and, therefore, aggregate both individual socioeconomic characteristics and transport and land use features (Ben-Akiva and Bowman, 1998; Ben-Akiva and Lerman, 1985; Handy and Niemeier, 1997; Miller, 1999).

The general formula of the utility-based accessibility measure can be defined as follows:

$$A_i = E\left(\max s \ \in \ SU_s\right) \tag{3.14}$$

Where s represents a choice alternative within a set of alternatives S, U_s the total utility of alternative s for each individual i. E stands for the expected value of the alternative that maximizes the individual's total utility (Ben-Akiva and Lerman, 1985).

According to Koenig (1980), utility approaches rely on two principles. The first is that people associate a cardinal utility for each choice option and choose the one that maximises their benefit as an individual. The second principle assumes that since a planner cannot evaluate all the factors that affect the utility associated with each alternative by a given individual, the utility can be represented as the sum of two components, a non-random (for the predictable factors) and a random (for the non-predictable factors). The non-random component is understood as the systematic utility and consists of observable attributes of the alternative (e.g. mode of transport, route, activity) and the individual (e.g. income, gender.) that are assumed to have an impact on the decision (Dong *et al.*, 2006). The random component, in turn, is defined as disturbance and represents the unobservable part of the utility (Dong *et al.*, 2006).

The utility that individual i obtains from alternative s can be defined as follows:

$$U_{is} = V_{is} + \varepsilon_{is}, \tag{3.15}$$

Where U_{is} is the utility that individual i obtains from alternatives $(i = 1, \ldots I;\ s = 1, \ldots, S)$; V_{is} is the non-random portion of the utility and ε_{is} denotes the factors that are not possible to be observed by the planner. Assuming that the ε_{is} of all alternatives are independently distributed (see Ben-Akiva and Lerman (1985) for details), we can adopt the logarithm of the denominator of the logit model, known as "logsum", as representative of the expected utility of an alternative within a set of alternatives (Ben-Akiva and Lerman, 1985; de Jong *et al.*, 2007; Dong *et al.*, 2006; Geurs and van Wee, 2004; Neutens *et al.*, 2011; Niemeier, 1997). The accessibility measure representing the maximum expected utility (UTIL) of the entire set of choices available to the individual is defined as follows:

$$UTIL_i = E\left(\max s \in SU_s\right) = \ln\left(\sum_{s=1}^{S} e^{V_s}\right) \tag{3.16}$$

$UTIL_i$ denotes the maximum expected utility of individual i, and V_s the observed transport, land use, and temporal utility components for the alternative s. One of the problems of utility-based accessibility measures is that they cannot be used to compare different regions since the function V_s is specified in different ways according to the planner and the context. To overcome this issue, several researchers suggest dividing the logsum by a marginal income utility coefficient (λ) to convert the accessibility score into monetary terms (Ben-Akiva and Lerman, 1985; Dong *et al.*, 2006; Geurs and van Wee, 2004). After this manipulation, de Jong *et al.* (2007) claims that it is possible to compute the total consumer surplus of a population by computing the weighted sum of utilities. In this case, the weights reflect the number of people in the population who have the same utility representation as to the individual in the sample.

Utility-based accessibility measures are not widely used in practice (Geurs and van Wee, 2004). Although they are based on theories such as consumer surplus and random utility, proposed in the 1970s and 1920s, respectively, applying these types of measures in transport projects only occurred after the 2000s (de Jong *et al.*, 2007).

3.3.3 Spatio-temporal measures

The spatio-temporal accessibility measures, also known as person-based measures, incorporate not only transport systems and land use features but also consider the individual's activities program and the effect of complex travel behaviour in the accessibility score(Kwan, 1998; Martens *et al.*, 2012; Neutens *et al.*, 2010). Such measures assess accessibility regarding an individual's ability to reach locations given the person's daily activity program and spatio-temporal constraints (Geurs and van Wee, 2004; Kwan, 1998). Unlike place-based measures of accessibility, spatio-temporal measures make no assumptions regarding the trip origin, i.e., they assume that trips for different purposes are successive events that start one after the other (Pirie, 1979). These measures can be calculated retrospectively from observed travel behaviour (Kwan, 1998) or computed prospectively for trips that have not yet happened, drawing on individuals' activities programs (Horner and Downs, 2014; Martens *et al.*, 2012; Neutens *et al.*, 2010).

The space-time measures are grounded on the time-geography theory proposed by Hägerstrand (1970) and later developed by Lenntorp (1976). In his seminal paper "What about people in regional science?", Hägerstrand challenged approaches that determined the behaviour of an aggregate population based on probabilistic models and drew attention to people's behaviour at the micro-level. As suggested by the title of the paper, Hägerstrand was interested in better understanding larger-scale urban phenomena by focusing on individuals (Patterson and Farber, 2015).

The geography of time theory proposed by Hägerstrand (1970) suggests that as individuals interact and participate in activities, they are confronted with the inseparability and sparse nature of space and time (Neutens *et al.*, 2011). That is, the events that make up an individual's existence have both spatial and temporal attributes, allowing them to participate in events at a single location in space at a given time (Miller, 1991). Moreover, according to Hägerstrand (1970), individuals' activities are often mutually exclusive. Activities must occur within a certain duration, at certain times and places, and together with certain groups of other individuals and equipment, which implies being chained together in a non-exchangeable sequence.

Hägerstrand (1970) identified three types of spatio-temporal constraints that limit the realization of the individual's sequence of activities. The capability constraints limit the activities of individuals due to their physiological capabilities, such as sleeping and eating, and available resources, such as, for example, owning a private vehicle or not. Coupling constraints define where, when, and for how long an individual has to join other individuals, tools or equipment in space and time to carry out activities (production, consumption, transaction). Authority constraints refer to the institutional and social context, including laws, rules, norms, and other regulations that imply that specific areas are only accessible for certain people to perform specific activities. According to Miller (2006), these constraints and activity patterns vary substantially concerning key social factors such as socioeconomic status, lifestyle, life cycle, household size and organization, vehicle availability and gender.

Hägerstrand (1970) also classifies activities into fixed and flexible/discretionary. Fixed activities cannot be easily rescheduled or relocated (e.g. work, education, medical appointments). For example, people generally work in a specific location for a certain period of time. Similarly, an individual's home has a fixed location and requires presence at regular intervals for maintenance (cooking, cleaning the house, childcare) (Miller, 2006). On the other hand, flexible activities can be more easily rescheduled and/or can take place in more than one location (e.g. shopping, leisure); however, there are also limits. For example, outlets have limited hours and few locations, or one cannot socialise if friends are not available (Miller, 2006)). Fixed activities act as space-time anchors because other (discretionary) activities must occur in the temporal intervals between fixed activities (Neutens *et al.*, 2011).

Spatio-temporal measures rely on concepts such as space-time paths, space-time prism (STP), potential path area (PPA), daily potential path area (DPPA), and feasible opportunities set (FOS) (Hägerstrand, 1970; Kwan, 1998; Miller, 1991, 1999; Neutens *et al.*, 2008). Three orthogonal axes represent a space-time region: a two-dimensional plane formed by the x and y axes and the z-axis representing the time variable (Hägerstrand, 1970). For example, an individual who is located at the point with coordinates (x_i, y_i, z_i), is located in space at coordinates x_i and y_i and at the moment z_i in time (Miller, 1991). As time elapses, the individual's spatio-temporal path can be traced, making it possible to understand how they navigated through space-time (Neutens *et al.*, 2011). If the individual moves through space at higher speeds, the slope of their space-time path will be more horizontal, meaning that the individual is exchanging less time for more space (Figure 3.2) (Miller, 1991).

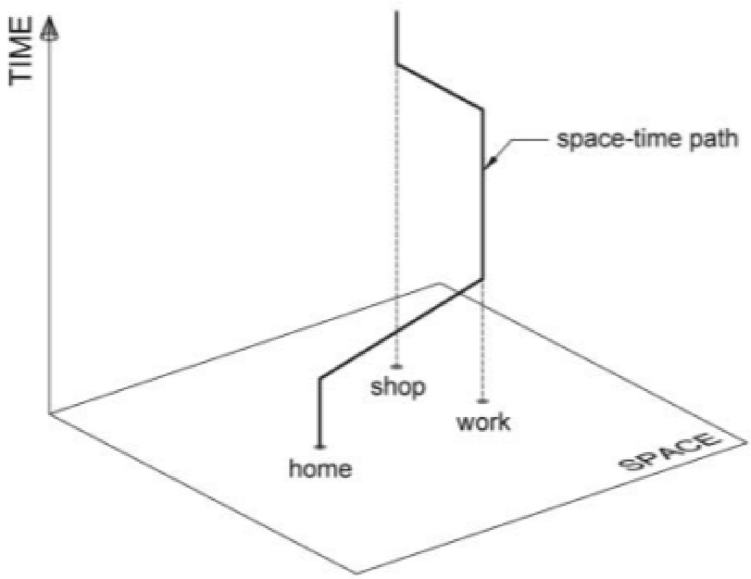


Figure 3.2: Schematic representation of the space-time path

Source: Farber *et al.* (2013)

The space-time prism (STP) (Figure 3.3) represents all the spatio-temporal paths an individual can take, i.e. the set of locations in space-time that are accessible to the individual given the location and duration of fixed (mandatory) activities, the distance to discretionary activities of interest, a time budget for participation in these discretionary activities and the speed allowed by the transport system (Burns, 1979; Hägerstrand, 1970; Miller, 1999; Neutens *et al.*, 2011). The STP determines the necessary but not sufficient conditions for virtually all human interactions (Hägerstrand, 1970; Miller, 1999).

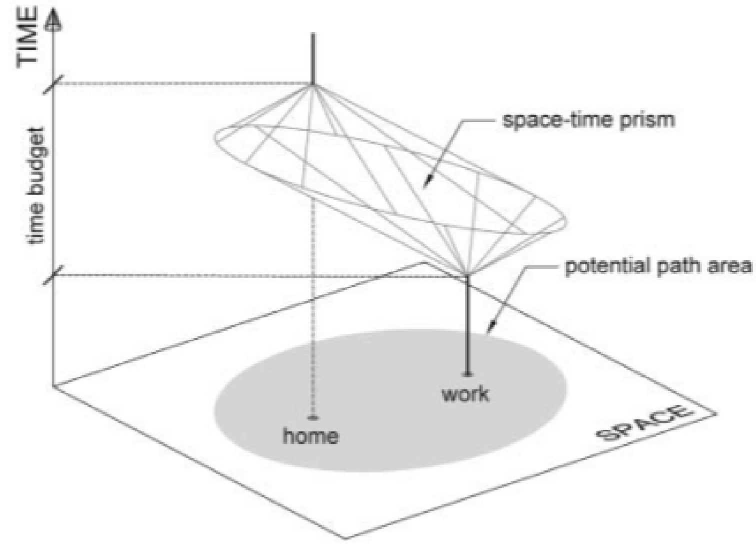


Figure 3.3: Schematic representation of the space-time prism and the PPA

Source: Farber *et al.* (2013)

The mathematical formulation provided by Kwan and Hong (1998) and Neutens *et al.* (2010) of the STP may clarify the accessibility measures presented later in this section. Consider that individual s with a schedule of successive mandatory activities ordered chronologically at anchor locations p_i, p_{i+1}. For any pair of consecutive fixed activities at locations p_i and p_{i+1}, there is a time budget available for performing the discretionary activity of $t_{i+1} - t_i$, where t_i is the earliest possible departure time from the mandatory activity p_i, and t_{i+1} is the latest possible arrival time at the mandatory activity p_{i+1}. In this sense, the space-time prism can be mathematically defined as follows (Kwan and Hong, 1998):

$$STP = \left\{(q,t) \mid \left(t_i + t_{p_i q} \leq t + \overline{T} \leq t_{i+1} - t_{qp_{i+1}}\right)\right\} \tag{3.17}$$

$$(t_q^o \leq t + \overline{T} \leq t_q^c) \tag{3.18}$$

Where t is the time at which the discretionary activity takes place; t_{p_iq} is the travel time from the anchor location p_i to the location q of the discretionary activity; $t_{qp_{i+1}}$ is the travel time from the location q of the discretionary activity to the next anchor location of the mandatory activity p_{i+1}; $\overline{T}$ is the minimum duration of the discretionary activity; t_q^o is the time that the activity q opens; and t_q^c the time that the activity q closes.

The planar projection of the SPT on the x - y geographical axes is called the potential path area (PPA). The PPA captures all activity locations that the individual can access given its time and space constraints (Kim and Kwan, 2003). One can say that the available time for calculating the PPA is the individual's time budget for discretionary activities, minus the travel time from the fixed activity to the discretionary activity and from the discretionary activity to the next fixed activity. This time interval, in turn, has to be greater than the minimum time of the activity duration (Kwan and Hong, 1998; Lenntorp, 1976; Miller, 1991) and must be available within the working hours of that activity.

If there are n consecutive pairs of fixed activities in a day, a series of PPAs for the day can be specified as $PPA_1,\ \ PPA_2\ \ \ldots,\ \ PPA_n$. The overlap of PPAs corresponding to successive pairs of fixed activities within a person's activity program creates the daily potential path area (DPPA) (Figure 3.4) and the feasible opportunity set (FOS) within the DPPA (Kim and Kwan, 2003; Kwan and Hong, 1998; Neutens *et al.*, 2010)). The FOS within the DPPA is defined by Kwan and Hong (1998) as:

$$FOS = \{q|(q,t) \in STP\} \tag{3.19}$$

Based on the spatio-temporal framework and the concepts previously described, several spatio-temporal accessibility measures have been derived. Neutens *et al.* (2010) proposed three categories of spatio-temporal accessibility measures. The first category, referred to by Neutens *et al.* (2010) as Lenntorp measures, examines whether the activity schedule of individuals is physically compatible with the spatio-temporal constraints imposed by the urban environment and fixed activities. This category comprises the following accessibility measures: the volume of the STP ($VSTP$), area of the PPA (or DPPA) ($APPA$), length of the transport network arcs within the DPPA (LEN), number of opportunities within the FOS (NUM), and the cognitive feasible opportunities set ($CFOS$).

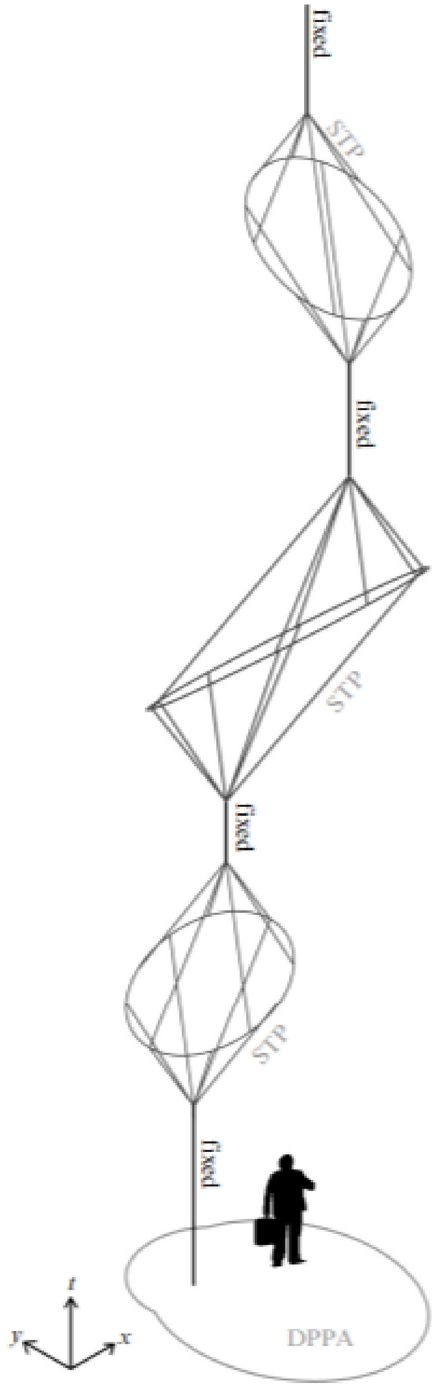


Figure 3.4: Daily Potential Path Area (DPPA) representation

Source: Neutens *et al.* (2010)

The second category arises from the combination of Lenntorp's measures and the works of Burns (1979) and Miller (1999) and comprises three measures: proximity of opportunities in DPPA ($NUMD$), weighted sum of opportunities (WA), and possible activity duration of opportunities in DPPA (DUR). The third category, in turn, called Burns-Miller measures, is based on the works of Burns (1979) and Miller (1999) and includes the following measures: aggregated utility of opportunities in DPPA ($BAGG$), maximum utility of opportunities in DPPA ($BMAX$), expected maximum utility of opportunities in DPPA ($BTRANS$).

Lenntorp measures

Volume of the space-time prism or Potential Path Area

The first operationalisation of spatio-temporal accessibility measures was done by Lenntorp (1976)'s model called PESASP (Program Evaluating the Set Alternative Sample Path). The PESASP simulation model relied on data on the location and opening hours of activities and frequency and speed of public transport to assess the extent to which spatio-temporal constraints allowed the execution of the individual's activity program (Neutens *et al.*, 2011). PESASP analytically calculated the volume of the space-time prism and PPA size by confronting a series of hypothetical activity programs with various transport and activity supply scenarios to determine which parts of the city and, inferentially, groups of people had good or poor access to opportunities (Lenntorp, 1976; Miller, 2007; Pirie, 1979).

Subsequently, Burns (1979) assessed the effects of changing travel speed and individuals' time constraints on the space-time prism (STP). According to Burns Burns (1979), the STP volume, or its projection on the x - y axis, i.e., the area of the STP, represents the freedom of individuals to engage in activities, i.e., their spatio-temporal autonomies. The first methods used to calculate the STP (and consequently PPA) were mathematical or geometric were not able to represent a complex travel environment (Kwan and Hong, 1998; Neutens *et al.*, 2011). Such methods assumed a constant and uniform speed across the urban environment, disregarding the fact that trips are made only across roads and, consequently, traffic conditions and speed limits.

The computational and method constraints limited the complexity of the first spatio-temporal accessibility measures to the volume of the space-time prism ($VSTP$) and the area bounded by the PPA ($APPA$) (Burns, 1979; Lenntorp, 1976; Miller, 2007; Neutens *et al.*, 2011). Subsequently, advances in STP volume calculation were made by Neutens *et al.* (2008), who developed a hybrid GIS (georeferenced information system) and CAD (computed-aided design) method.

Similar to all spatio-temporal measures, $VSTP$ and $APPA$ vary according to transport speed, individuals' time budget, and distance between origin and the destinations where the STP is anchored (Farber *et al.*, 2013). By simply measuring the spatial extent of the area reachable by the individual given their spatio-temporal constraint, $VSTP$ and $APPA$ measures do not consider some spatio-temporal properties of the prism, such as the geographical distribution and temporal availability of opportunities (Kim and Kwan, 2003).

Number of Opportunities and Length of Network Arcs

Although the introduction of the conceptual framework for spatio-temporal measures occurred in 1970 by Hägerstrand (1970), the development of this type of measures in the subsequent decades was limited, mainly due to the lack of robust geocomputational tools and the unavailability of georeferenced travel data at the individual level (Neutens *et al.*, 2011). However, advances in geographic information systems (GIS) from the 1990s onwards have allowed the development of more sophisticated spatio-temporal measures than the PPA (or DPPA) area or STP volume (Neutens *et al.*, 2011; Patterson and Farber, 2015). Miller (1991) was the first to develop a GIS procedure to calculate spatio-temporal constructs. Based on the structure of the transport network, Miller (1991) computed the network time prism (NTP), potential path trees (PPTs), and potential network area (PNA) (Neutens *et al.*, 2008). The potential network area, or PPA of the network, shows the paths (arcs) in the transport network that are feasible to travel and the intersections (nodes) that an individual can reach. Two types of more sophisticated spatio-temporal accessibility measures have emerged from the advances in GIS procedures: the length of network arcs (LEN) and the number of opportunities within the DPPA (NUM) (Kwan, 1998; Páez *et al.*, 2012). LEN is calculated as follows:

$$LEN = \sum_{N} L_l R(l) \tag{3.20}$$

$$R(l) = \begin{cases} 1, \text{ if } l \in DPPA, \\ 0, \; otherwise \end{cases} \tag{3.21}$$

Where l is an arc of the transport network (N), L_l denotes the length of arc l and the function $R(l)$ assumes one if arc l is within the DPPA and 0, otherwise. Although LEN is an improvement compared to past measures, Kwan and Hong (1998) showed that spatio-temporal accessibility measures derived from geometric methods, such as STP volume, PPA area, and even LEN, may not have a direct relationship with the number of opportunities accessible to an individual due to not considering the spatial distribution of opportunities in their computation.

To circumvent this issue, Kwan and Hong (1998) proposed a measure that accounts for the number of opportunities (NUM) within the DPPA (equivalent to the FOS). NUM considers the irregular spatial distribution of activities and aspects of the transport network, such as the speed and direction of streets. NUM is defined as follows:

$$NUM = \sum_{q} R(q), \tag{3.22}$$

$$R(1) = \begin{cases} 1, \text{ if } q \in DPPA, \\ 0, \; otherwise \end{cases} \tag{3.23}$$

$R(q)$ assumes one if activity q is within the DPPA and 0 otherwise.

However, it is worth noting that the NUM measure considers only the number of opportunities within the DPPA, disregarding the temporal availability of these opportunities and their compatibility with the individual's time budget (Kim and Kwan, 2003). Furthermore, NUM considers that all activities within the FOS are equally desirable (Neutens *et al.*, 2010).

Cognitive feasible opportunity set

According to Kwan and Hong (1998), many studies that apply spatio-temporal accessibility measures consider that feasible opportunity set is so vast that many of the alternatives contained therein are not perceived as relevant by the individual because of limited knowledge of city areas and/or lack of familiarity with the potential activities location. Kwan and Hong (1998) argue that an individual may not have the cognitive ability to assess the number of opportunities in the feasible opportunity set (FOS). Also, there are preferences inclinations and aversion for certain activities. In this sense, the spatial configuration of the FOS may be very different from what individuals actually experience in their daily lives.

Kwan and Hong (1998) incorporated the spatio-temporal an cognitive constraints of the individual to develop an operational method in GIS to generate a set of spatial opportunities more restrictive and relevant than the FOS. The accessibility measure proposed by them is the number of opportunities within the cognitive feasible opportunity set ($CFOS$), which comprises the spatial opportunities familiar to the individual and reachable given her spatio-temporal constraints. Two aspects are important in this process: spatial knowledge or familiarity with various city areas and preference or aversion for specific locations, which indicate the individual's tendency to prefer or avoid certain city areas when seeking a particular type of activity. The cognitive set of opportunities is defined as follows:

$$COS_{iq} = \{m | m \in F_{iq} \; and \; m \; \notin P_{iq}\} \tag{3.24}$$

Where F_{iq} is the set of spatial alternatives (discretionary opportunities q) known to individual i, defined by some measure of familiarity or awareness; P_{iq} is the set of spatial alternatives that the individual s will not consider due to his/her location aversion or preference. The COS_{iq} contains the spatial alternatives familiar to the individual i that will be considered by her/him. The cognitive set of feasible opportunities $CFOS_{iq}$ for an individual i seeking a discretionary activity, q is specified by the intersection of the FOS_{iq} and the COS_{iq}:

$$CFOS_{iq} = \{ \; c \mid \; c \; \in (FOS_{iq} \cap COS_{iq})\} \tag{3.25}$$

Hybrids of Lenntorp and Burns-Miller measures

The measures presented in the previous section build on Lenntorp (1976)'s work about STP representation. A new category of spatio-temporal measures has emerged from merging Lenntorp (1976)'s approach with the extension of Burns (1979)'s work by Miller (1999).Miller (1999) brought together three different perspectives on accessibility measures: (i) the constraint-oriented approach implemented by spatio-temporal prisms (STP); (ii) gravity-type accessibility measures that rely on a spatial interaction framework to assess the set of available opportunities given their attractiveness and the travel costs of reaching them; and (iii) utility measures that assess the individuals' welfare.

The Lenntorp and Burns-Miller's hybrid measures comprise only Miller (1999) first two perspectives: spatio-temporal prisms and gravity-type accessibility measures. Unlike Lenntorp's pure measures, Lenntorp and Burns-Miller's hybrid measures and express the desirability for activities rather than only the cardinality in the FOS (Neutens *et al.*, 2010). The desire by the opportunities is assessed by differentiating them based on travel time, attractiveness and/or possible time duration (Kim and Kwan, 2003; Neutens *et al.*, 2011).

Proximity of opportunities in DPPA

The proximity of opportunities in DPPA ($NUMD$) is a variation of Lenntorp's NUM measure. $NUMD$ adds an element of spatial proximity to the FOS opportunities using a negative exponential impedance function according to the transport mode (Neutens *et al.*, 2010). Unlike NUM, where only the number of opportunities is computed, $NUMD$ distinguishes between opportunities based on their proximity to important anchor locations (e.g., work, home) and based on a distance decay function (Neutens *et al.*, 2010). The $NUMD$ measure is defined as follows:

$$NUMD = \sum_{q} \exp\left(-\lambda_m \frac{t_{p_i q} + t_{q p_{i+1}}}{2}\right) R\left(q\right) \tag{3.26}$$

λ_m denotes the parameter of the distance decay function for the transport mode m.

Weighted sum of the opportunities

The weighted sum of opportunities (WA) measure (Kwan, 1998) is another variation of the NUM measure. Unlike $NUMD$, where the value of opportunities is discounted according to an impedance function, WA weights the opportunities giving their attractiveness. Mathematically, WA is defined as:

$$WA = \sum_{q} a_q R(q) \tag{3.27}$$

Possible activity duration of opportunities in DPPA

According to Kim and Kwan (2003), people hardly travel long distances to participate in activities for just one or two minutes. A certain amount of activity time is required to make the trip worthwhile and make the accessibility measurement more realistic. Kim and Kwan (2003) suggest accounting for the number of accessible opportunities and the duration an individual can spend at the opportunity location given its spatio-temporal constraints. Kim and Kwan (2003) considered not only delays and congestions on the roads but also a minimum activity participation time, a travel time threshold, and the working hours of opportunities to build the space-time prism. In this sense, Kim and Kwan (2003) propose a third hybrid Lenntorp and Burns-Miller measure: the possible activity duration of opportunities in DPPA (DUR) (Neutens *et al.*, 2010). The DUR measure is defined as follows:

$$DUR = \max q \left[\left(t_q^e - t_q^s \right) R(q) \right] \tag{3.28}$$

Where t_q^e and t_q^s denote the earliest possible start time for discretionary activity q and the latest possible end time for the same activity, respectively. Unlike the previously presented measures, DUR is based on maximisation operation. Thus, DUR depicts the temporal freedom of the individual to visit opportunities in the DPPA (Neutens *et al.*, 2010).Kim and Kwan (2003) apply DUR jointly with the WA measure. They calculate the accessibility score by computing the weighted sum of opportunities according to their areas multiplied by the possible activity duration for all PPAs within the individual's DPPA.

Burns-Miller measures

The Burns-Miller measures are based on the extension of Burns (1979)'s work by Miller (1999). Burns (1979) suggested introducing the utility-based measures within the space-time perspective. Burns (1979) proposed a conceptualisation of accessibility benefits in space-time that accounts for the attractiveness of activity locations, the possible duration of the activity, and the cost of spatial separation. Miller (1999), in turn, extended the conceptualization proposed by Burns (1979) to meet the axiomatic framework proposed by Weibull (1976). Burns-Miller type measures differ from Lenntorp's measures because they express quantity and benefit from FOS opportunities. The benefit (utility) is assessed by differentiating between opportunities based on travel time, attractiveness and/or possible activity duration (Neutens *et al.*, 2010).

Aggregated utility of opportunities in DPPA

The aggregated utility of opportunities in DPPA measure ($BAGG$) combines two components. The first component, derived from $NUMD$, refers to the spatial proximity of opportunities within the DPPA computed by a negative exponential impedance function specific to the transport mode; and the second component, originated from the WA measure, incorporates the attractiveness of the opportunities (Neutens *et al.*, 2008). The $BAGG$ is defined as follows:

$$BAGG = \sum a_q \left(t_q^e - t_q^s\right) \exp\left(-\lambda_m \frac{t_{p_i q} + t_{q p_{i+1}}}{2}\right) R\left(q\right) \tag{3.29}$$

The $BAGG$ measure expresses the benefit obtained by the individual from the possibilities of choice to participate in activities in space-time (Miller, 1999; Neutens *et al.*, 2011). The score of $BAGG$ will be higher if the set of alternatives within the DPPA contains more options (Neutens *et al.*, 2011, 2010).

Maximum utility of opportunities in DPPA

According to Neutens *et al.* (2011), sometimes the goal is not to calculate the aggregate benefit obtained from the entire set of alternatives in the FOS but rather to identify the best benefit that of one activity within the FOS. In this case, only the most beneficial activity is important (Miller, 1999; Neutens *et al.*, 2010). In this sense, a variation of the previous measure would be the maximum benefit obtained from an activity in the FOS ($BMAX$), defined as:

$$BMAX = \max\{q\}\left[a_q \left(t_q^e - t_q^s\right) \exp\left(-\lambda_m \frac{t_{p_i q} + t_{q p_{i+1}}}{2}\right) R\left(q\right)\right] \tag{3.30}$$

Expected maximum utility of opportunities in DPPA, based on the logit decision process

The third Burns-Miller measure shares the $BMAX$ maximisation character, but is grounded on a different theory from the previous ones (Neutens *et al.*, 2010). The utility approach suggests that an individual associates a cardinal utility for each alternative within a set of options and then selects the one with the highest utility (Koenig, 1980). The expected maximum utility of opportunities in DPPA ($BTRANS$) measure incorporates the $UTIL$ accessibility measure within the STP (Miller, 1999). $BTRANS$ is defined as follows:

$$BTRANS = \ln \sum_{q} \exp\left[a_q \left(t_q^e - t_q^s\right) \exp\left(-\lambda_m \frac{t_{p_i q} + t_{q p_{i+1}}}{2}\right) R\left(q\right)\right] \tag{3.31}$$

The $BTRANS$ equation can also be expressed in monetary terms if divided by a travel cost coefficient (or income marginal utility). The $BTRANS$ measure expresses the level of desirability rather than the size of a set of activity options (Neutens *et al.*, 2011).

3.4 Assessing Accessibility measures

This section assesses the 24 accessibility measures described according to the analytical framework developed in section 2. Considering that no accessibility measure perfectly meets all the defined criteria, it was decided to rate each measure according to their degree of adherence to the criterion evaluated (4 - Very Good, 3 - Good, 2 - Fair, 1 - Poor). At the end of this section, table **??** presents the scores obtained by each measure in each criterion and their respective final score.

3.4.1 Theoretical criteria assessment

- **Criterion 1:** Does the measure focus on access to activities?

$DMIN_{Trans}$, $TMIN_{Trans}$, $DCBD$, $VSTP$, $APPA$, LEN, and DUR measures indirectly account for access to activities. $DMIN_{Trans}$ and $TMIN_{Trans}$ focus on access to transport infrastructure and not to activities. Although the ease of access to the transport system is related to the ease of access to activities, it is not directly connected to the goal of social inclusion, which is access and participation in activities. Similarly, the $DCBD$ implicitly assumes that all activities are located in the CBD or that urban residents value only accessibility to activities in the CBD.

The $VSTP$ and $APPA$ measures, respectively, assume that larger prisms or PPA are associated with more opportunities for participation. Similarly, the LEN assumes that the greater the length of the transport network within that area, the more locations are likely to be accessible. However, the number of opportunities will vary according to the land-use spatial distribution and density, which is not captured by these measures. DUR presumes that the more available time an individual has, the more activities he/she will engage in. However, DUR does not systematically assess the actual number of activities available to the individual and may fall into the same problem as $VSTP$ and $APPA$. For example, individuals may be forced to travel considerable time/distance to access relevant opportunities because there may be no activities close to their location. The other accessibility measures primarily focus on access to activities and are adequate to assess the risk of TRSE according to criterion 1.

- **Criterion 2:** What is the unit of analysis used by the measure?

From the social inclusion perspective, accessibility measures should adopt the individual as the unit of analysis since the objective to be sought is to guarantee a minimum level of participation by the individual in the normal activities of the society. The most adherent with this criterion is the spatio-temporal measures category, which uses individuals as the analysis unit to derive their spatio-temporal prisms and FOS. Utility-based measures can also use individuals as the unit of analysis (Martens and Golub, 2012); however, the measured outcome can only be presented in an aggregated manner or for the average person in the sample.

In general, place-based measures usually calculate the accessibility score for a given spatial unit, such as a census tract. By aggregating by spatial unit, place-based measures suggest that all individuals inhabiting that area have the same level of accessibility. However, this is an undesirable limitation. Individuals differ considerably in terms of time budget, and capabilities and may experience different levels of accessibility living in the same zone (Handy and Niemeier, 1997; Neutens *et al.*, 2011). Time allocation and activity preferences vary enormously according to socio-demographic characteristics such as age, gender, employment status, life stage, and income (Miller, 2006). In addition, data aggregation bias (Kwan, 1998; Levinson and King, 2020) may cause scale and zone effects, and the choice of the representative point of the spatial unit is often problematic. From a social inclusion perspective, this is an inappropriate approach due to ecological fallacy.

In order to address this issue, place-based accessibility measures should ideally use the individual's location as a reference (Páez *et al.*, 2012). Although this is not the best option, it avoids aggregation bias and does not make general assumptions regarding the individuals' accessibility of a given location. However, the place-based measures $CONT$, $PTPR$, $GRAV_{Comp}$, and CUM_{Comp} cannot use a point in space as the unit of analysis, only an area.

- **Criterion 3:** Does the measure incorporate the individual's constraints, abilities, and perceptions?

Accessibility measures that do not use the individual as a unit of analysis, such as place-based, do not incorporate individual constraints, abilities and perceptions in the accessibility computation. Place-based measures rely on the logic of physical proximity, where distance is assumed to have the same meaning for all individuals. They ignore personal spatio-temporal constraints that could limit the individual from experiencing the suggested level of accessibility assigned to them (Horner and Downs, 2014; Kwan, 1998; Miller, 2006; Neutens *et al.*, 2011, 2010). Place-based measures mask individual differences and focus on the transport and land-use system outcomes rather than on individuals' appropriation of these resources to pursue the life they value (Miller, 2006). Boisjoly and El-Geneidy (2016) argue that it is possible to consider individual aspects in place-based measures by stratifying the data. However, individual characteristics are still aggregated by groups rather than individually, not fully meeting criterion 3. Furthermore, this stratification is usually based on observed travel, violating criterion 9.

Utility-based measures capture the perception of individuals regarding the activities, disregarding the perception regarding the transportation system. In the random utility approach, the impedance of the model is estimated deterministically based on the generalised cost of the shortest path to each destination. Consequently, these models fail to capture individual perceptions towards transport (Malekzadeh and Chung, 2019). On the other hand, due to the flexibility of random utility models, it is possible to incorporate other individual characteristics, such as income, into the modelling. Utility-based measures also face the stratification problem previously mentioned. Unless a logsum function for each individual is derived, what does not happen in practice, the same individual perceptions and constraints regarding activities are estimated for the group of individuals modelled. Moreover, other characteristics and their impact on accessibility are incorporated through observed travel behaviour or assumptions regarding behaviour. In this sense, utility-based measures meet criterion 3 only partially.

Measures that use decay functions and activity attractiveness factors ($GRAV$, $NUMD$, and WA) make assumptions regarding individuals' perception of the separation cost between origin and destinations and the activities' attractiveness (Geurs and van Wee, 2004; Kwan, 1998; Neutens *et al.*, 2010). From a social inclusion perspective, this is undesirable because it is not assessing the ability of individuals to access activities, but rather it is making assumptions about their perceptions. Neutens *et al.* (2010) found that making assumptions in accessibility measures regarding how individuals evaluate travel time can significantly influence equity outcomes.

Measures that account for opportunities competition, such as $GRAV_{Comp}$ and CUM_{Comp}, although considering the probability of a person converting a resource (accessible job opportunities) into well-being (getting a job), they do not assess the adherence of the worker's skills to the job requirements (Martens and Golub, 2012). This is an essential element in assessing the real chance of an individual participating in a work activity.

There is a consensus in the literature that spatio-temporal measures provide a more accurate notion of individual accessibility to opportunities than the other categories (Patterson and Farber, 2015). Spatio-temporal measures assess the extent to which a person can convert transport and land use resources into capabilities, given their physical and contextual constraints on movement and participation in mandatory activities (Horner and Downs, 2014; Kim and Kwan, 2003; Lee and Miller, 2019; Martens and Golub, 2012; Neutens *et al.*, 2011, 2010). The premise that distance has the same meaning for all individuals is relaxed in spatio-temporal measures. Proximity to an activity no longer depends solely on physical distance or travel time but also on individuals' time budgets (Neutens *et al.*, 2010). Kwan (1998) found that incorporating individual constraints into accessibility measures produces results quite different from those generated by place-based measures.

NUM and $CFOS$ measures are potentially helpful in assessing the TRSE risk because they incorporate individuals' characteristics and restrictions without making assumptions regarding their perception. The $CFOS$ measure, in particular, proves even more relevant by incorporating not only individuals' spatio-temporal constraints but also their cognitive ability to evaluate the set of choices in the FOS (Kwan and Hong, 1998). Accessibility measures that include all potential destinations are an overestimated representation of the accessibility individuals experience in their daily lives (Handy and Niemeier, 1997; Kwan and Hong, 1998).

It is worth noting that several individual aspects that influence individuals level of accessibility are not incorporated by any of the measures described, such as the perception about the urban environment, fear of crime and insecurity during the trip and while accessing public transport stops, fear of harassment, discrimination and prejudice, educational level, physical condition, and social status.

- **Criterion 4:** How sensitive is the measure to the ease or disutility (distance, time, and monetary cost) an individual faces in moving between an origin and a destination?

$CONT$ and $PTPR$ measures fail to incorporate the transport element in the analysis of accessibility and are therefore unable to capture the disutility faced by individuals due to the spatial separation. Accessibility measures that use transport stop as destination ($DMIN_{Trans}$ and $TMIN_{Trans}$) do not capture the impedance caused by the transport system (Malekzadeh and Chung, 2019). Distance measures, such as $DMIN$ and $DCBD$ are unable to capture travel time variations (e.g. congestion) (Neutens *et al.*, 2010) and suggest equal accessibility values regardless of the time of day. $TMIN$, on the other hand, is unable to articulate the distance metric and can only consider time as a separating element. Despite conceptually referring to the balancing time, the BT measure allows adaptations to incorporate the distance as an element of transport impedance.

Accessibility measures that use gravity-type impedance functions ($GRAV$, $GRAV_{Comp}$, $NUMD$, WA, $BAGG$, $BMAX$ and $BTRANS$) are more sensitive to the disutility faced by individuals in accessing destinations. Such functions emphasize the effect of distance deterrence and assume that although individuals can travel anywhere in the city to access an opportunity, they are less likely to travel to distant locations (Talen and Anselin, 1998). CUM, CUM_{Comp}, NUM and $CFOS$ measures are more insensitive to variations in travel time since they have a cut-off distance or time ((Neutens *et al.*, 2010). This group of measures suggests that the impedance faced by the individual to access a very distant activity, but still within the cut-off time, is the same as to access a very close activity. Thus, cumulative opportunity measures are very sensitive to the cut-off time, distance, or monetary cost adopted, making their score vary considerably depending on the value chosen (Ben-Akiva and Lerman, 1979; Black and Conroy, 1977; Handy and Niemeier, 1997; Ingram, 1971; Kwan, 1998; Neutens *et al.*, 2010; Pirie, 1979). The cumulative opportunities type measures (CUM and CUM_{Comp}) have an advantage over those that use impedance functions of the gravitational type because they are not based on observed travel behaviours.

The CUM and CUM_{Comp} measures can account for monetary cost instead of travel time or distance as the cut-off. It means that they can consider the impedance represented by monetary costs when individuals use the transport system (El-Geneidy *et al.*, 2016). The $GRAV$ and $GRAV_{Comp}$ measures also are able to account for monetary cost jointly with travel time as impedance, as proposed by Bocarejo S. and Oviedo H. (2012). However, the introduction of monetary cost in the gravity-type functions is made from the observed travel behaviour of individuals, which is undesirable according to criterion 9 of the analysis framework.

Utility-based measures are sensitive to transport characteristics such as distance, travel time and monetary costs (Dong *et al.*, 2006; Martens and Golub, 2012). Unlike other accessibility measures, which need to make a calculation for each transport mode assessed, UTIL measures have the advantage of including all modes of transport in the mode choice model from which the logsum is derived (Dong *et al.*, 2006).

- **Criterion 5:** How sensitive is the accessibility measure to land use aspects, such as quality, quantity, and spatial distribution of activities?

$DMIN_{Trans}$, $TMIN_{Trans}$ and $DCBD$ measures take into account only the transport component and fail to incorporate the influence of land use on accessibility (Malekzadeh and Chung, 2019). $DMIN$ and $TMIN$ do not consider the variety, quality or quantity of activities available to people (Handy and Niemeier, 1997) and therefore are only impacted by the spatial distribution of nearby activities. Moreover, $DMIN$, $TMIN$, DUR, $BMAX$ and $BTRANS$ are more oriented to finding the best opportunity option and therefore are little sensitive to variations in the quantity and spatial distribution of activities (Neutens *et al.*, 2010). Utility-based measures ($UTIL$) can cope with changes in the distribution and quality of activities depending on the specification of the logsum model adopted by the planner (van Wee, 2016). The $GRAV$, WA and Burns-Miller measures ($BAGG$, $BMAX$ and $BTRANS$) are able to articulate differences in activity quality. However, they only do so through a composite attractiveness index, which means that distinct qualities (size, services offered, waiting times etc.) are aggregated into a single value (Miller, 2018; Neutens *et al.*, 2011). On the other hand, $GRAV_{Comp}$, CUM, CUM_{Comp}, BT, NUM, $CFOS$ and $NUMD$ treat activities as equal without distinguishing their attractiveness. It is an advantage to some extent as they do not make assumptions regarding individuals' perceptions about activities' attractiveness. The $CONT$ and $PTPR$ measures, depending on how they are specified, may consider only the quantity of opportunities within the spatial unit analysed, or they may vary according to the service capacity of the activities.

Spatio-temporal measures examine the activities that are part of an individual's daily life and are able to capture the demand for these activities dynamically in space and time (Miller, 2007; Neutens, 2015). However, some spatio-temporal measures ($VSTP$, $APPA$, LEN and DUR) are only sensitive to mandatory activities, i.e. those necessary for building the spatio-temporal prism and disregard discretionary activities' diversity, spatial distribution, and qualities. A limitation of the people-based measures worth highlighting is the ability to assess accessibility only for non-mandatory or discretionary activities. The only group of mandatory activities considered (but not assessed) by these measures is those in which the individual already regularly participates and shapes his/her prism-time-space. This family of measures cannot capture an important dimension of accessibility which is accessibility to employment (and study) (Martens and Golub, 2012).

Spatio-temporal measures (NUM, $NUMD$, WA, and $CFOS$) examine the activities that are part of an individual's daily life and capture the demand for these activities dynamically in space and time (Miller, 2007; Neutens, 2015). Nevertheless, spatio-temporal measures are limited to assessing only non-mandatory or discretionary activities. The only group of mandatory activities considered (but not assessed) is those individuals who already participate daily and shape their STP. Spatio-temporal measures cannot capture an important dimension of social inclusion: job accessibility (Martens and Golub, 2012).

Spatio-temporal measures are demand-oriented and therefore do not consider the capacity constraints of activities and, consequently, the effects of competition (Martens and Golub, 2012; Neutens, 2015; Neutens *et al.*, 2011). Only a few place-based measures, BT, $GRAV_{Comp}$ and CUM_{Comp} are able to confront demand with the supply of opportunities, i.e. the probability of the individual converting accessible opportunities (employment, school, health) into participation (Martens and Golub, 2012). This is a relevant advantage, given that participation in the labour market is an important factor in social inclusion.

- **Criterion 6:** Does the accessibility measure capture the effects of fluctuations in travel time and availability of opportunities throughout the day with a single calculation?

Distance-based measures such as $DMIN$, $DMIN_{Trans}$ and $DCBD$, and the $TMIN_{Trans}$, $CONT$, and $PTPR$, fail to articulate the effects of fluctuations in travel time throughout the day, $DCBD$, $DMIN_{Trans}$ and $TMIN_{Trans}$ measures, by not taking activities into account in their calculations, do not incorporate the effects of the availability of opportunities throughout the day. To capture the temporal variability of activities throughout the day, $DMIN$, $CONT$, and $PTPR$ must be computed several times at different periods of the day. The place-based measures BT, $GRAV$, $GRAV_{Comp}$, CUM, CUM_{Comp}, and the utility-based measure, on the other hand, can consider the effects of fluctuation in travel time and availability of activities throughout the day if multiple calculations are made. Spatio-temporal measures, on the other hand, are also able to consider these effects, but with only a single measurement (Neutens *et al.*, 2010; Páez *et al.*, 2010).

- **Criterion 7:** Does the measure account only for single trips/activities or consider complex chains of multiple trips/activities between origins and destinations?

$DMIN_{Trans}$ and $TMIN_{Trans}$ measures cannot evaluate trips to destinations since they are measures of accessibility to public transport. In addition, the $CONT$ and $PTPR$ measure, as they only contemplate the land use component of accessibility, are also unable to be evaluated regarding criterion 7.

Place-based measures assume that all possible trips that contribute to the individual's accessibility start from a single origin, usually the home or workplace. It means that they underestimate accessibility levels because they disregard multi-purpose trips with multiple stops (Kwan, 1998; Neutens *et al.*, 2010). Alternatively, accessibility levels may be overestimated by place-based measures because they do not capture the spatio-temporal constraints of individuals and activities (Neutens *et al.*, 2010). Spatio-temporal measures account for multi-purpose trips and trip chaining without problems (Lee and Miller, 2019; Neutens *et al.*, 2010).

- **Criterion 8:** Does the measure use the utility as a parameter for calculating the accessibility score?

Due to the expensive tastes issue exposed by Martens and Golub (2012), measures that use welfare as a parameter are not suitable to evaluate distributional aspects of transport interventions. The adoption of the utility as the distributive rule is associated with a counterintuitive distribution, suggesting distributing more resources to people with expensive tastes, usually the wealthiest ones, and fewer resources to those who are used to living in more difficult situations, with few resources available. In this sense, we can discard the UTIL measure and the Burns-Miller spatio-temporal measures ($BAGG$, $BMAX$, and $BTRANS$).

- **Criterion 9:** Is the measure derived from observed travel behaviour and carried out activities, or does it assess what people can potentially achieve without replicating biases of past travel behaviour patterns?

Accessibility measures for assessing the risk of social exclusion should be based on what people can potentially achieve rather than what they actually do (travel behaviour).

From a social inclusion perspective, people are interested not only in the activities they access but also in the range of activities they could potentially achieve (Martens, 2016b; van Wee, 2016). If we only consider what people do (observed travel behaviour), a person who works remotely and does not go out for other activities because they prefer to spend their time at home, but at the same time can access a vast range of activities, would be considered at risk of social exclusion. Measures that use a decay function with calibrated parameters according to observed travel behaviour replicate biases (Handy and Niemeier, 1997) and compromise identifying opportunities that individuals can potentially access. Therefore, measures that use an impedance function calibrated based on observed travel behaviour ($GRAV$, $GRAV_{Comp}$, $NUMD$, $BAGG$, $BMAX$, and $BTRANS$) are not suitable for assessing the TRSE risk. The most common practice is to adopt the negative exponential decay function (Geurs and van Wee, 2004; Handy and Niemeier, 1997; Kwan, 1998; Shen, 1998; Thill and Kim, 2005). According to Handy and Niemeier (1997), most OD survey deals exclusively with revealed travel behaviour and pays little attention to the reasons behind the behaviour and the preferences and constraints of individuals (Handy and Niemeier, 1997). It is worth noting that it is possible to adopt other decay functions that do not require calibration, such as the linear (1/d) one. The CUM measure, in general, does not require calibration. However, some studies (see Páez *et al.* (2010, 2012) suggest varying the cut-off time according to a particular group's location or socioeconomic profile. In this case, the CUM measures fall into the same problem of replicating biases of the observed behaviour observed in the calibration of the cut-off time parameter. Utility-based measures ($UTIL$) assume that accessibility level results from the set of transport choices and rely on observed travel behaviour to derive the log sum function (Martens and Golub, 2012).

The place-based and spatial-temporal measures that do not use an impedance function calibrated based on travel behaviour are suitable to assess TRSE risk according to criterion 9. The spatio-temporal measures $VSTP$, $APPA$, LEN, NUM, WA and $CFOS$ assess the possibilities of travel and participation in activities given individuals' spatio-temporal constraints (Kwan, 1998; Martens and Golub, 2012). By calculating the FOS of individuals based on their place of residence and mandatory activities they undertake, NUM and $CFOS$ assess the degree to which the individual can transform resources (the transport system and the spatial distribution of activities) into participation options given their spatio-temporal constraints.

- **Criterion 10:** Does the measure assume a maximization strategy in the choice process?

Considering that individuals value the range of options available to them, measures that adopt an optimisation or maximisation strategy tend to return only the accessibility to the opportunity perceived as most advantageous. This, in turn, prevents the evaluation of all the individual's participation possibilities and, therefore, compromises the TRSE risk assessment. Place-based measures $DMIN$, $TMIN$, $DMIN_{Trans}$, and $TMIN_{Trans}$ assume that people act as maximizers and choose the best option, i.e., the closest activity or public transportation stop. In addition, BT assumes that the relevant activities for the individuals are always those closest to their reference location.

Utility-based measures ($UTIL$) also seek to identify the optimal set of activities and the utility derived from this set when an individual participates in these activities. Thus, they fail to define the individual's feasible opportunities set (Martens and Golub, 2012). The spatio-temporal measures DUR, $BMAX$, and $BTRANS$ are also grounded on the maximization principle. The other unmentioned measures imply that the individual's accessibility increases if he/she has more opportunities to choose from. Because these measures make fewer assumptions regarding the choice rule adopted by people, they are compatible with the idea of freedom of choice and the difference between individual preferences (decision rules) (Neutens *et al.*, 2010).

3.4.2 Usability and Interpretability criteria assessment

- **Criterion 11:** How easily is the measure operationalised regarding data, models and techniques, time, and budget availability?

The $CONT$ and $PTPR$ measures consider only land use aspects and, therefore, are relatively easy to implement with a basic GIS knowledge (Neutens, 2015). Distance and time-based measures also do not impose much difficulty (Lee and Miller, 2019). The $DMIN$, $TMIN$, $DMIN_{Trans}$, and $TMIN_{Trans}$ measures only require information of the activities (or transport stops) closest to the reference location and the calculation of the distance and time between them. It can be easily executed in GIS or online and require very low computational power. The calculation of the $DCBD$ measure is perhaps one of the easiest and can be done in a single measurement of the distance to the city centre.

CUM and BT measures require information regarding the spatial distribution of opportunities and the travel time to these opportunities from the reference location. They do not require data regarding the activities' attractiveness and do not require the adoption of a transport deterrence function with a calibrated parameter. $GRAV$ measure is more complex, requiring data about the quantity, spatial distribution, and attractiveness of activities (Neutens, 2015). In addition, $GRAV$ is more complex to calculate due to the calibration of the impedance function parameter according to the OD survey data (Owen and Levinson, 2015). However, the parameter of the impedance function is usually already calculated in transport and land-use models applied in the planning process (ex: four-step model) (Geurs and van Wee, 2004).

The remaining place-based measures account for competition ($GRAV_{Comp}$ and CUM_{Comp}). Such measures are the most difficult to calculate among the place-based measures. These measures require origin-destination data of individuals in the region, the number of people in each zone, the proportion of these people seeking the evaluated opportunity in the other zones (demand) and the number of opportunities (supply) in each of the zones. In the case of the $GRAV_{Comp}$ measure, there is the additional difficulty of defining and calibrating two impedance functions, one for each model. Among the measures that incorporate competition, BT is the simplest to calculate, followed by CUM_{Comp} and $GRAV_{Comp}$.

Utility-based measures are derived from transport models used to estimate an individual's modal choice (Niemeier, 1997; van Wee, 2016). Utility-based measures follow the trend of seeking more disaggregated and complex representations of accessibility. However, this is done at the expense of ease of operationalisation. As complexity and disaggregation increase, computational costs also increase (Handy and Niemeier, 1997). In this sense, $UTIL$ measures are limited in terms of spatial resolution since destinations must be aggregated to reduce the set of choices or rely on a random selection of alternatives (Páez *et al.*, 2012). According to Páez *et al.* (2012), this random selection is dubious due to spatial autocorrelation concerns and the implications for multinomial logit models' Irrelevant Alternatives Interdependence (IIE) property. Because of the complexity involved in its formulation and calculation, the UTIL measure is hardly used in real, dense urban areas (Curl *et al.*, 2011; Lee and Miller, 2019; Miller, 2018).

Like utility-based measures, space-temporal measures present a very high difficulty in operationalisation. Such difficulty is derived from the demand for detailed data on an individual's activities and trips program, the high computational power required, and the scarcity of feasible operational algorithms to deal with the complexity of real transport networks (Geurs and van Wee, 2004; Kwan, 1998; Miller, 1999; Neutens *et al.*, 2011, 2010). The existing toolkits to assess spatial-temporal measures are generally built based on top existing GIS packages, which require know-how and availability of specific GIS software and, therefore, may impose financial barriers to use (Neutens *et al.*, 2011).

The required individuals' time budget data is usually unavailable in conventional OD surveys. Methods for collecting such data require individuals to recall and report their actions during a past (typical) time window and rely on individuals' good memory to recall them later (Miller, 2006). By requiring individuals to report normal activities that occur during some typical period, objections arise as to the definition of what normal activities are and what a typical period is. Also, many individuals are unwilling to report certain activities or do not report short trips and the number of stops during the trip (Miller, 2006). The $CFOS$ measure adds an extra complexity layer by requiring individuals to report and interpret what activities are in their cognitive field.

The high computational intensity required by these models derives from the combinatorial explosion of options. Decisions such as choosing the number of activities within a period, the sequencing and timing of these activities, mode of transport, and chosen routes are interrelated, implying that the number of options is exponential for the number of choice options (Ben-Akiva and Bowman, 1998; Miller, 2006). Spatio-temporal measures often simplify the transportation component to reduce computational intensity by replacing distance in the network by Euclidean distance, excluding delays and congestion and impedance factors such as modal shift time and travel costs (Geurs, 2018). Nevertheless, the computational intensity remains high, and traditional statistical methods can explore only a tiny subset of possibilities within the opportunities set (Miller, 2007, 2006). In this sense, spatio-temporal accessibility measures are limited to small regions (neighborhoods) and population subgroups (Geurs and van Wee, 2004; Kwan, 1998; Lenntorp, 1976; Neutens *et al.*, 2011). Consequently, the use of these measures is compromised when large generalizations are desired (Neutens, 2015; Páez *et al.*, 2012). Perhaps because of all these difficulties, only a few attempts to operationalise space-temporal measures have been made so far (Kim and Kwan, 2003).

Among the most difficult spatio-temporal measures to implement is $BTTRANS$, which, because of the utility component within the space-time prism, faces the problems of implementing the space-time measures and the utility-based measure. In addition, the $BTTRANS$, $BMAX$, $BAGG$, and WA measures require additional information on the attractiveness of activities, and the $BTTRANS$, $BMAX$, $BAGG$, and $NUMD$ require the definition and calibration of the decay function parameter.

- **Criterion 12:** How easily policymakers and researchers can communicate and interpret the measure?

The most easily communicated and interpreted place-based measures are $DMIN$, $TMIN$, $DMIN_{Trans}$, $TMIN_{Trans}$, $DCBD$, $CONT$, $PTPR$, BT and CUM. The interpretation of these measures is in absolute units and is relatively straightforward (Neutens, 2015). For example, $DMIN$, $TMIN$, $DMIN_{Trans}$ and $TMIN_{Trans}$, results in the distance or minimum time to the nearest public transport stop or opportunity. $DCBD$ is the distance from the reference location to the city centre. $CONT$ is the number of activities within the unit of analysis, and $PTPR$ is the number of these activities per capita. BT, in turn, is the travel time taken to reach the number of activities equal to the number of people in the unit of analysis, and CUM is the number of opportunities reached within a given time, distance or monetary cost of travel. Policymakers, researchers and the general public will face no difficulties in understanding the results of these measures. Among the measures that assess the range of opportunities open to individuals and also the influence of the transport component on accessibility, CUM is unanimous among researchers in ease of interpretation and communication (Curl *et al.*, 2011; Geurs and van Wee, 2004; Koenig, 1980; Neutens, 2015; Neutens *et al.*, 2010).

The $GRAV$ measure is more difficult to interpret than the other location-based measures (Geurs and van Wee, 2004). The main difficulty in interpreting this measure lies in the weights of opportunity attractiveness and the weighting done by the impedance function (Geurs and van Wee, 2004). The outcome of the mathematical formula of $GRAV$ does not tell us anything (Geertman and Ritsema Van Eck, 1995). Unlike measures that can be interpreted in absolute values, $GRAV$ only allows it to be interpreted in relative terms by normalising the values found (Neutens, 2015). Thus, the CUM measure ends up being the most widely used in practice (Curl *et al.*, 2011).

The interpretation of the accessibility measures that consider the competition ($GRAV_{Comp}$ and CUM_{Comp}) is not as problematic as its operationalisation. These measures provide a result from 0 to 1 for each spatial unit analysed. To determine whether the unit is better, worse or equal to the average of the rest of the region analysed, it is compared with the proportion of people employed in the region. For example, if there is an unemployment rate in the region of 6%, it means that 94% (0.94) of the population is employed. If a spatial unit has an score greater than 0.94, it has better accessibility than the average.

The complexity of the utility concept makes this type of measure challenging to understand even for accessibility researchers (Miller, 2018; van Wee, 2016). These measures cannot be clearly explained without reference to relatively complex theories (behavioural models of consumer surplus) that most planners and policymakers do not understand (Koenig, 1980). One of the problems faced by $UTIL$ is the impossibility of comparing different utility functions by region or neighbourhood (Handy and Niemeier, 1997) unless it is transformed into monetary terms. However, both the absolute value provided by the measure and the monetary value lack a physical/spatial interpretation (El-Geneidy *et al.*, 2016). Perhaps because of all these drawbacks, utility-based measures are not often used in practical applications (de Jong *et al.*, 2007; Dong *et al.*, 2006; Niemeier, 1997).

Among the spatio-temporal measures, a group of measures are quite simple to communicate since their absolute results can be directly interpreted. This is the case of the $APPA$, LEN, NUM, $CFOS$ and DUR measure, which can be understood as, the area in the analysed region that the individual can reach throughout the day, length of roads within that area, number of activities within that area, set of activities that individuals perceive as feasible within the area, and time available for participation in discretionary activities. The $VSTP$ measure also does not face significant problems of interpretation and communication; however, it requires reference to space-time theory.

The evolution of spatio-temporal measures has brought about increasingly complex algorithms, hindering the direct interpretation of these measures (Neutens *et al.*, 2011). The $NUMD$ and WA measures lose a bit of their ability to communicate due to the introduction of the impedance function and the attractiveness of activities, respectively. The Burns-Miller measures ($BAGG$, $BMAX$ and $BTRANS$) increase the interpretation complexity considerably relatively the other measures by joining the weighting by the impedance function with the attractiveness of activities and the utility theory. In general, the need to use GIS software and complex algorithms to calculate spatio-temporal measures makes them difficult to communicate and disseminate to policymakers, transport professionals and the general public (Neutens *et al.*, 2011). Because of all these difficulties, utility-based and spatio-remporal measures are less popular in practical applications (Curl *et al.*, 2011).

Tables A.1 and A.2 summarising the qualitative assessment of all 24 accessibility measures according to the 12 proposed criteria can be found in Appendix A.

3.5 Discussion

The importance given to each of the criteria will vary according to the context, the purpose of the analysis, the budget available, the availability of data, equipment and staff, and the target audience. Although no accessibility measure meets all the criteria, we can discuss the best choices based on the analysis conducted in the last section.

Considering that the goal to be achieved is social inclusion, that is, enabling individuals to participate in the everyday activities of the society in which they are inserted, a critical criterion in the choice of measures is criterion 1, which assess whether the measures focus on assessing access to activities directly. In this sense, measures such as $DMIN_{Trans}$, $TMIN_{Trans}$, $DCBD$, $VSTP$, $APPA$, LEN, and DUR fail to account for the number of opportunities the individual can participate in.

A second crucial criterion in assessing the risk of transport-related social exclusion is whether the measure uses welfare/utility as a parameter to measure the level of accessibility (criterion 8). As discussed, the use of welfare is linked to the issue of expensive tastes/adaptive preferences, which can generate counterintuitive and distorted results on how the distribution of resources of a given transport policy should be made. In this sense, $UTIL$, $BAGG$, $BMAX$ and $BTRANS$ can produce misleading results about the equitable accessibility distribution in the population.

The third critical criterion that can help us narrow down the set of appropriate measures is criterion 10, which assesses whether the measure is based on maximisation strategies in the choice process. Since social inclusion is linked to participation in activities, accessibility measures should assess all options available to the individual. Furthermore, they should avoid making assumptions regarding the decision rule adopted by individuals when making their choices since the factors which will influence such decisions will vary from person to person. Because of this, we can exclude those measures based on optimization strategies that, supported by assumptions about individual preferences, return as outcome only the "best activity". Measures such as $DMIN$, $TMIN$, BT and DUR fail to consider the range of options available to individuals. Still, regarding the assumption about individual preferences, measures that incorporate the attractiveness of activities based on their qualities make assumptions about how individuals perceive them (discussed in criterion 3) and, therefore, fail to account for the heterogeneity and differences in people's preferences. $GRAV$, $GRAV_{Comp}$ and WA face this issue.

When assessing TRSE, the replication of travel behaviour biases in accessibility measurements is not desirable (criterion 9). Many people would like to access a set of activities but do not do so due to limitations imposed by the transport network and land-use system or their own limitations. On the other hand, there are also situations of people who do not access certain activities because they do not want to but could do so. In this case, only the first individual is socially excluded. Therefore, we are interested in assessing what individuals could potentially achieve and not what they do since it tells us very little about their capabilities and freedom of choice. In this sense, measures that adopt a deterrence function and rely on observed travel behaviour to calibrate its parameter (such as $NUMD$, GRAV, $GRAV_{Comp}$) may not be the best option to be used in TRSE risk assessment.

The criteria discussed so far were the most critical to TRSE risk assessment. The other criteria are more related to the trade-offs between robustness, usability and interpretability. Accessibility measures to assess the TRSE risk are more realistic if they use the individual as the unit of analysis (criterion 2), capture individual capabilities, skills, and perceptions that influence accessibility (criterion 3), are sensitive to the disutility faced by the individual when using the transport system (criterion 4), incorporate variations in quantity, spatial distribution and competition for activities (criterion 5), capture fluctuations in travel time throughout the day (criterion 6) and can account for complex travel chains (criterion 7). However, there is a trade-off since the more of these aspects the measure incorporate, the greater the operationalisation complexity is (criterion 11) and more challenging it to communicate and interpret (criterion 12).

The least sophisticated and realistic measures that were not dismissed by the critical criteria are $CONT$ and $PTPR$. As these measures do not consider the transport component of accessibility, their assessment against the criteria 4, 5, 6 and 7 becomes impractical. In addition, they are impossible to be calculated for the individual or a point in space, limiting their analysis to a spatial unit. They also do not consider aspects related to individual capacities and perceptions. In this sense, despite not breaking any of the critical criteria previously discussed, $CONT$ and $PTPR$ do not prove to be good measures to assess transport-related social exclusion due to their excessive simplicity.

The most sophisticated measures are NUM and $CFOS$. These measures are computed at the individual level, incorporate differences in individuals' spatio-temporal constraints, variability in the quantity and spatial distribution of activities, and can capture both fluctuations in travel times and opportunities working hours, as well as multipurpose and multistop trips. $CFOS$ also accounts for the cognitive ability of individuals in recognizing feasible opportunities to be accessed. However, all this robustness comes at a price. NUM and $CFOS$ are extremely difficult to calculate and require enormous computing power, and there is a scarcity of suitable operationalisation algorithms. The few existing operationalised methods are limited to specific GIS packages, are usually expensive, and require trained professionals. In addition, detailed data on the individual's activity program is unavailable and highly costly and complex to collect. In this sense, the application of NUM and $CFOS$ measures are limited to small scales, such as neighbourhoods and small groups of individuals. From a theoretical point of view, a disadvantage of NUM and

$CFOS$ is the impossibility of assessing accessibility to fixed activities, such as employment.

Although not as sophisticated as NUM and $CFOS$, CUM presents operationalisation advantages. From a theoretical perspective, these measures can consider the disutility in the distance, time, or monetary cost the individual faces and are sensitive to variations in the quantity and spatial distribution activities. CUM does not make assumptions regarding individuals' perceptions and can capture the accessibility fluctuations throughout the day due to variations in travel time and opportunities' working hours using multiple measurements. CUM permits using a point in space as the analysis unit, thus avoiding spatial aggregation biases. CUM accounts for mandatory and discretionary activities, but they do not capture trip chaining or individuals' capabilities, skills, and perceptions.

The CUM measure is more straightforward to operationalise than NUM and $CFOS$. CUM only requires information on activities' quantity, spatial distribution, and travel time between origin and destination pairs. In general, opportunities data is easily accessible in socio-demographic surveys, and travel times can be calculated without much difficulty with open-source applications and APIs. In addition, the computational power demanded to calculate CUM is considerably lower than NUM and $CFOS$, allowing the application at the macro scale, such as entire cities and metropolitan regions. Due to the less powerful equipment requirements, CUM is much easier to be implemented by transportation planning agencies than NUM and $CFOS$.

In sum, $CFOS$ and NUM are the most sophisticated measures from a theoretical point of view and represent the individuals' possibilities of participation in a more detailed manner. However, the operationalisation difficulty the inability to assess accessibility to mandatory activities limit their practical application. The CUM measure allows the assessment of accessibility in large urban regions and to mandatory and discretionary activities. Although easily operationalised, CUM loses realism for presenting simplifications in its formulation. $CFOS$, NUM, and CUM are easily communicated and interpreted by researchers, policymakers, and the general public.

3.6 Conclusions

With the increasing popularization of accessibility in the various fields of science, several accessibility measures have emerged to assess the most different types of issues. The existing works in the literature on accessibility measures, in general, focus on discussing and examining how different factors shape an individual's accessibility score and rarely delve into the suitability of these measures to assess the pursued policy goals. However, this is a critical issue since the selected measures can considerably influence the outcomes of a given policy. Measures may generate distorted and inadequate answers for the investigated problem if disconnected from pursued objectives. Besides, there is a tendency in the literature to develop increasingly complex accessibility measures, data, and computational power demanding. However, this trend is far from the real purpose of informing public policy.

This chapter assessed 24 accessibility measures according to their theoretical adherence with social inclusion goals and their usability and interpretability. Such assessment relied on 12 theoretical criteria and two usability criteria. From a methodological point of view, the main contribution of this work has been to provide a systematic overview of how and to what extent each of the main accessibility measures found in the literature is suitable for assessing TRSE.

We identified that the best measures for TRSE assessment are CUM, NUM, and $CFOS$. These measures assess the range of activities available to individuals, do not make value judgments regarding how they perceive activities or transport impedance and are not based on observed travel behaviour. Moreover, they are sensitive to variations in the quantity and spatial distribution of opportunities and the disutility individuals face to overcome the separation between an origin and a destination. They do not suffer from measurement biases created by differences across individuals' personal utilities/satisfactions. Nevertheless, it is worth noting that the dismissal of the other accessibility measures in the analysis does not mean that they are worthless; they are simply not adequate to assess TRSE risk as CUM, NUM and $CFOS$.

The selection of one of the three measures will vary according to the size of the study area, the type of activity to be assessed, and the amount of data and computational power available. In cases where the analyst intends to assess the accessibility throughout the day to non-mandatory activities of small groups or small urban regions, and detailed data regarding individuals' activity diaries and high computational power are available, the application of the NUM measure is the most recommended. The $CFOS$ measure is even more appropriate than NUM when data regarding how individuals perceive the availability of opportunities. Both measures use the individual as the unit of analysis, can capture interpersonal differences in spatio-temporal constraints, trip chaining, and articulate accessibility variation throughout the day. The CUM measure, on the other hand, is more recommended when there are limited data availability and low computational power. Additionally, CUM is recommended to assess large urban regions, make generalizations regarding accessibility patterns, and assess the possibilities of participation in mandatory activities.

Although CUM does not consider the capabilities and restrictions of individuals in accessing activities, it is still valuable in portraying the transport and land use resources available to individuals without violating any critical criteria that may distort or lead to erroneous results in the TRSE assessment. CUM allows planners to identify locations where lack of participation in society occurs primarily due to spatial issues such as lack of transport options and/or opportunities. If measured continuously throughout the day, they allow identification of how temporal variation in transport and opportunities supply may restrict participation options for individuals inhabiting certain locations. In addition, CUM permits assessing employment accessibility that NUM and $CFOS$ do not allow.

There is no best approach capable of capturing all the elements that may influence the ability of individuals to access and participate in activities. Even the $CFOS$ and NUM measures that incorporate certain interpersonal differences, many aspects that are not measured may restrict individuals' opportunities set, such as fear, perceived quality of public transport, educational level, physical condition, social status, discrimination, and prejudice. Furthermore, all accessibility measures reviewed in this chapter focus on a macro or mesoscale and do not cover local aspects such as walkability and built environment features, often cited in the literature as determinants of local activities participation. In this sense, we recommend applying CUM measures at the macro scale, if possible, NUM or $CFOS$ for selected small groups within the study area more likely to face social exclusion. Furthermore, we suggest combining these measures with local accessibility measures and questionnaires and interviews to capture issues that are difficult to measure objectively, such as perception, fear, discrimination, and prejudice.

We assessed the theoretical and practical aspects that make accessibility measures appropriate for assessing TRSE. However, more empirical evidence of applying the selected measures is needed to validate our findings. Finally, are the outcomes of a simple measure such as CUM as effective as the complex measures such as $CFOS$ and NUM? Does the additional cost of calculating such measures outweigh the additional robustness benefits they provide? Such questions merit further research.

Chapter 4

Does Better Accessibility Help to Reduce Social Exclusion? Evidence from the City of São Paulo

Abstract

Most of the transport equity and TRSE studies assume that increasing accessibility levels lead to increased activity participation and, therefore, a social exclusion reduction. Although this assumption makes sense from the theoretical point of view, it is not sure that it is valid in practice.Previous studies investigating the accessibility-participation relationship were inconclusive, indicating that increasing accessibility has a limited impact on activity participation levels if any. Moreover, the existing empirical evidence in the literature are scarce in the Global South context, are merely correlational and fail to infer causality between both variables. This chapter focuses explicitly on inferring a causal relationship between accessibility levels and activity participation in a Global South context. Three poisson regression model associated with an instrumental variable identification strategy was used to assess the causal effect between accessibility and participation in total, mandatory and discretionary activities in the city of São Paulo.The cumulative opportunities measure is adopted due to its simplicity, ease of interpretation and because it is the accessibility measure most used in practice by policymakers. The three models showed a highly significant, strong correlation between an individual's accessibility level and his/her actual participation in total, mandatory and discretionary activities. The magnitude of accessibility effect on activity participation was comparable to the effect of the socio-demographic and locational variables. This

finding reinforces the narrative that TRSE is not merely a spatial phenomenon but also an individual one.

4.1 Introduction

The lack of access to critical opportunities in society is associated with substantial economic and social costs (United Nations, 2016). Studies on the relationship between accessibility and social issues date back 1970s (e.g. Black and Conroy (1977); Wachs and Kumagai (1973)). However, the interest in assessing transport policies and investments from the perspective of accessibility has emerged only in the last two decades (Martens, 2016a). Currently, accessibility measures have been used to assess the distributional effects of transport policies and identify groups at risk of social exclusion (Allen and Farber, 2020; Boisjoly and El-Geneidy, 2017a; Curl *et al.*, 2011; Páez *et al.*, 2010). Accessibility is treated by transport-related social exclusion (TRSE) research as a key indicator for the number of opportunities available to individuals, where it is assumed that greater levels of accessibility lead to higher levels of participation and thus less social exclusion.

Despite the theoretical consistency of this statement, most of the accessibility measures used in practice to assess TRSE risk account only for some of the components (Kamruzzaman *et al.*, 2016; Pyrialakou *et al.*, 2016) that shape an individual's possibilities of participation and do not capture the complex social interactions, perceptions, and behaviours that influence activity participation (Bantis and Haworth, 2020; Curl *et al.*, 2011; Luz and Portugal, 2021; Martens, 2016b).

The empirical research that has tested the accessibility-activity participation relationship did not indicate a consensus regarding its validity. Some articles found that accessibility levels are associated with higher activity participation levels, while others found that this relationship is weak or not statistically significant. Some papers found that his relationship may be valid for a specific type of activity, transport mode or accessibility measure, and others found a negative relationship. This lack of consensus may suggest that it is not sure that TRSE evaluations using accessibility measures produce reliable results. In other words, the impact of policy interventions based on accessibility measures aimed to reduce TRSE may be overestimated. In order to collect empirical evidence on the relationship between accessibility and activity participation/travel generation, this chapter carried out a systematic literature review.

In December 2021, a search was conducted in the scientific base Scopus with the following combination of words: (("accessibility") AND ("activity participation" OR "participation in activit*" OR "activity rates" OR "trip generation" OR "trip making" OR "trip rates") in the Title, Abstract or Keyword of the papers. The search returned 289 documents. After applying the filter for documents of the type "article" in Journals and written in English, 211 documents remaining in the sample. Then, the titles of the 211 articles were read. Those that did not investigate the relationship between accessibility and the activity participation or trip-making were discarded. After reading the title and the abstract of the articles, 171 articles were excluded from the group, remaining only 40 documents. After careful examination of the 40 articles full text, 17 were excluded in the review, leaving 23 papers. After that, we used a forward and backward snowball method to complement the systematic literature review.Fifteen additional articles were identified. The final literature reviewed thoroughly consists of 38 articles.

Very few of the previous studies that tested the relationship between accessibility and participation in activities were from the perspective of social inclusion and/or equity (Allen and Farber, 2020; Cheng *et al.*, 2019; Fransen *et al.*, 2018b). Most of the studies adopt an aggregated approach and fail to control people's interpersonal heterogeneity adequately. Moreover, most studies focus on Global North contexts, and empirical evidence is scarce for Global South contexts.Only two of these studies discussed the relationship between accessibility and activity participation curve shape. Finally, and perhaps most importantly, none of the reviewed studies on the accessibility-activity participation relationship inferred causality.

In order to fill these literature gaps, this chapter aims to test the causal relationship of accessibility on activity participation in a Global South context. The city of São Paulo, Brazil, was adopted as a case study. We assessed the accessibility-activity participation relationship according to the type of activities accessed, mandatory activities (work and education), discretionary activities (leisure, shopping or having a meal), and total activities (without distinguishing between purpose). Unlike more recent studies on the topic that tend to use more sophisticated measures of accessibility, we decided to use the cumulative opportunities accessibility measure (CUM). We choose CUM measure not only because of its simplicity, ease of interpretation and popularity among policymakers, but also to assess whether even one of the simplest accessibility measure, which only accounts for transport and land use components, is able to influence the level of participation in activities. Aspects such as ease of operationalisation and interpretation are crucial for the accessibility measure to be used by planners, especially in a Global South context where transport agencies face data limitations and have poorly qualified technical staff. Disaggregation is another feature that distinguishes our research from previous studies that employed place-based accessibility measures. We assessed the accessibility-activity participation association while considering the individual's accessibility level and his/her sociodemographic characteristics.

Although from the TRSE perspective, we should focus the accessibility analysis on the potential of opportunities that people can participate in, the measurement of realised activity participation may be a good way to understand the appropriateness of an accessibility measure to assess TRSE (Luz and Portugal, 2021). When we look at the accessibility-activity participation relationship of a single individual, we can expect that some people have may have a wide range of participation opportunities but not participate in any activities. However, testing this relationship for a whole population is expected to be valid (Luz and Portugal, 2021)). In this view, a helpful accessibility metric for assessing TRSE must be associated, at least in part, with the activity participation level.

Our findings suggest a highly significant, strong correlation between an individual's accessibility level and his/her actual participation in total, mandatory and discretionary activities. Based on our results, we argue that low accessibility levels may severely restrict individuals' life chances and put them at risk of TRSE. TRSE assessment, even when conducted using place-based accessibility measures that account only for transport and land use components, such as CUM, provides reasonable and consistent outcomes.

The remainder of this chapter is organised as follows. Section number two presents a review of the literature on transport-related social exclusion and a summary of findings of previous studies that have tested the relationship between accessibility and participation in activities. Section number three describes the study area, the data used and the reasons for selecting the cumulative opportunities measure for the study. Section four introduces the methodology used and describes the instrumental variable identification strategy adopted to infer causality between accessibility and participation. Section five presents the findings, and section six the chapter's conclusions.

4.2 Background

4.2.1 Transport-Related Social Exclusion (TRSE) and Accessibility

An individual is socially excluded if "he or she is geographically resident in a society, but for reasons beyond his or her control he or she cannot participate in the normal activities of citizens in that society and he or she would like to so participate" (Burchardt *et al.*, 1999, p. 229). According to Preston and Rajé (2007), a helpful way of thinking about social exclusion is to reshape Amartya Sen's theory of entitlement. Sen suggests that famines are not caused by a lack of food but by a lack of access to food (Sen, 1983). Similarly, social exclusion is not due to lack of social opportunities but to lack of access to those opportunities (Preston and Rajé, 2007). In this sense, the transport system plays a critical role in providing people access to activities, services, and opportunities dispersed in space (Farrington, 2007).

Given that the primary purpose of transport systems is to provide access to opportunities that people have reason to value (Allen and Farber, 2020; Martens, 2016a,b; van Wee and Geurs, 2011), individuals can be deprived of participation in society and be at risk of transport-related social exclusion (TRSE) if these systems fail to achieve their purpose. Formally, transport-related social exclusion is defined as the process by which people are prevented from participating in the economic, political, and social life of the community because of reduced accessibility to opportunities, services, and social networks, due to in whole or in part, to poor potential mobility (Kenyon *et al.*, 2002). It means that the partial or complete people's inability to traverse space limits individuals from reaching different opportunities, indicating accessibility poverty (Jeekel and Martens, 2017) which, in turn, can manifest itself in social exclusion (Luz and Portugal, 2021). Simply put, people at risk of TRSE are those in accessibility poverty. In this sense, transport policies aimed to promote social inclusion should increase the accessibility levels of those in accessibility poverty conditions (Luz and Portugal, 2021).

The accessibility notion was first introduced by Hansen (1959)) in the late 50s and defined as the "potential of opportunities for interaction." However, its link with social exclusion emerged with UK policymakers in the early 2000s with the publication of the iconic report "Making the Connections: Transport and Social Exclusion", launched by the Social Exclusion Unit (2003). The Social Exclusion Unit (2003) document brought a new narrative to accessibility notion: the ability of people to reach and take part in opportunities and activities normal for that society (Farrington and Farrington, 2005; Farrington, 2007; Social Exclusion Unit, 2003). From this point of view, accessibility is understood as an attribute of individuals in their interaction with the environment, considering how personal characteristics interact with the transport system, land-use, and political, economic, and social environment to shape the individuals' accessible opportunities set (Lucas, 2006, 2012; Luz and Portugal, 2021; Pereira *et al.*, 2017).

Recently, many transport equity and TRSE studies advocate for the application of the Capabilities Approach to express concepts such as the accessibility narrative brought by TRSE literature (Bantis and Haworth, 2020; Hananel and Berechman, 2016; Luz and Portugal, 2021; Martens, 2016b; Pereira *et al.*, 2017). According to those studies, the notion of accessibility as a human capability allows expressing the broad diversity of individuals and how they interact with transport and land use resources and the environment to determine people's participation opportunities (Luz and Portugal, 2021; Pereira *et al.*, 2017; Vecchio and Martens, 2021). Although beneficial to articulate the TRSE accessibility narrative theoretically, the idea of accessibility as a human capability faces at least two practical challenges (Pereira *et al.*, 2017).

The first is that understanding accessibility in terms of capabilities couples accessibility needs with the idea of social rights – called by Farrington and Farrington (2005) as "accessibility rights"–, which means that a minimum level of accessibility is necessary to satisfy individuals' basic needs (Farrington, 2007; Luz and Portugal, 2021; Pereira *et al.*, 2017). Although some attempts (e.g., Lucas *et al.* (2016); van der Veen *et al.* (2020)), the definition of what a "minimum level" of accessibility is and when the accessibility is below this threshold remains a practical and philosophical unresolved issue (Arranz-López *et al.*, 2019; Lucas, 2012; Lucas *et al.*, 2016; Pereira *et al.*, 2017; Pucci *et al.*, 2019; van der Veen *et al.*, 2020; van Wee and Geurs, 2011). The second challenge is that the notion of accessibility as a human capability requires one to address accessibility as a result of a combination of personal abilities and perceptions, transport and land-use resources, and the political, social and economic environment, which is a much more complex and multi-dimensional concept than those used in conventional transport studies (Luz and Portugal, 2021; Pereira *et al.*, 2017; Vecchio and Martens, 2021).

Despite the wide range of accessibility measures developed over time, such as infrastructure-based, place-based, utility-based and Spatio-temporal measures (Geurs and van Wee, 2004; Handy and Niemeier, 1997; Kwan, 1998; Neutens *et al.*, 2010), none of them alone can capture all the accessibility as a human capability nuances. Depending on the accessibility measure selected, some accessibility factors will be privileged while others neglected (Geurs and van Wee, 2004; Handy and Niemeier, 1997; Kamruzzaman *et al.*, 2016; Kwan, 1998; Martens, 2016b; Neutens *et al.*, 2010; Pyrialakou *et al.*, 2016). Different accessibility measures account for different facets of how individuals interact with the spatial structure and distribution of opportunities (Fransen *et al.*, 2018a). In this sense, different accessibility indicators will provide entirely different insights into the equitable distribution of opportunities (Neutens *et al.*, 2010) and, therefore, indicate different policy alternatives.

Most of the transport equity and TRSE studies assume that increasing accessibility levels lead to increased activity participation and, therefore, a social exclusion reduction. Although this assumption makes sense from the theoretical point of view, it is not sure that it is valid in practice. The accessibility measures applied by these studies account only for some of the components that shape an individual's possibilities of participation and may not capture the complex social interactions, perceptions, and behaviours that influence activity participation (Bantis and Haworth, 2020; Curl *et al.*, 2011; Luz and Portugal, 2021). It means that TRSE evaluations using conventional accessibility measures may lead to misleading results, such as overestimating the impact of a policy intervention aimed to reduce TRSE.

In this regard, a more in-depth understanding of the relationship between the most conventional accessibility measures and activity participation is necessary to define sufficient levels of accessibility and design effective policies to mitigate TRSE (Allen and Farber, 2020; Martens, 2016a). However, there has been little empirical research about whether popular accessibility measures are positively related to activity participation and less risk of social exclusion.

4.2.2 Accessibility and Activity Participation

Empirical Evidence

Measuring accessibility in all its dimensions is highly complex, and therefore, it is not certain that one accessibility indicator adequately captures all possibilities for participation in activities (Martens, 2016b). Empirical evidence on whether accessibility levels correlate with activity participation; and whether a given accessibility measure reflects the individuals' participation possibilities are scarce in the literature. More evidence is found outside the TRSE literature on the relationship between accessibility and trip making. Given that a trip is not an end in itself but more of a means to perform other activities (Cordera *et al.*, 2017), it is plausible that the number of trips made by an individual is directly related to the number of activities in which he/her participated (Allen and Farber, 2020; Merlin, 2015). Hence, the evidence provided by this group of studies is also helpful to understand if higher accessibility levels are related to more activity participation and, therefore, less social exclusion (Merlin, 2015). In total, 38 articles that studied the relationship between accessibility and activity participation and/or trip making were reviewed.

Evidence of the relationship under study is scarce for the Global South context, particularly in African and Latin American countries. Of the 38 articles reviewed, only five are in Global South countries (Cheng *et al.*, 2019; Ding *et al.*, 2016; Krasić and Novačko, 2015; Masoumi, 2021; Wang and Cao, 2017). Moreover, most of the studies (24) are related to travel forecasting and focus on understanding the relationship between accessibility and the number of trips made. Few studies focus on assessing the relationship between accessibility and activity participation (9 studies) (Allen and Farber, 2020; Bhat *et al.*, 2013; Ding *et al.*, 2016; Fransen *et al.*, 2018a; Golob, 2000; Lavieri *et al.*, 2018; Merlin, 2015; Wermuth, 1982; Zhang, 2005). Moreover, just a few of these studies have focused on social exclusion and equity aspects related to accessibility provision (Allen and Farber, 2020; Cheng *et al.*, 2019; Fransen *et al.*, 2018a). Five articles have examined the relationship between accessibility, trip generation and activity participation (Cheng *et al.*, 2019; Kitamura *et al.*, 2001; Næss, 2006; Schwanen *et al.*, 2007; Williams, 1989). Studies that focus on trip generation tend to adopt an aggregate approach, using zones as the unit of analysis. At the same time, most papers on activity participation utilise the individual or household as observation.

Most of the reviewed articles used location-based measures of accessibility. The most widely adopted accessibility measure was the gravity type (Allen and Farber, 2020; Bhat *et al.*, 2013; Cordera *et al.*, 2017; Ewing *et al.*, 1996; Fransen *et al.*, 2018a; Handy, 1993; Hanson and Schwab, 1987; Kitamura *et al.*, 2001; Lee and Goulias, 1997; Robinson and Vickerman, 1976; Thill and Kim, 2005; Vickerman, 1974; Wang and Cao, 2017; Williams, 1989; Zhang, 2005); followed by the measure of minimum or weighted distance or time to activities, transport stop or CBD (Cordera *et al.*, 2017; Downes and Morrell, 1981; Handy, 1996; Kitamura *et al.*, 1997; Krasić and Novačko, 2015; Kröger *et al.*, 2018; Lavieri *et al.*, 2018; Leake and Huzayyin, 1980; Lee and Goulias, 1997; Masoumi, 2021; Næss, 2006; Purvis *et al.*, 1996; Schwanen *et al.*, 2007; Tian and Ewing, 2017; Wu *et al.*, 2012) and by the cumulative-opportunities measure (Bhat *et al.*, 2013; Golob, 2000; Handy, 1996; Schwanen *et al.*, 2007; Thill and Kim, 2005; Tian and Ewing, 2017). Some authors adopted more simple place-based measures that account for only the land use component of accessibility (households density, population density, jobs density, area characteristics) (Calvo *et al.*, 2019; Masoumi, 2021; Merlin, 2015; Wermuth, 1982; Zhang *et al.*, 2019) or only aspects of transport infrastructure (Leake and Huzayyin, 1980; Seo *et al.*, 2013; Wu *et al.*, 2012). Other accessibility measures found in the literature are utility-based measures (Golob, 2000; Koenig, 1980; Seo *et al.*, 2013) and spatio-temporal measures, such as the volume and the number of activities within the space-time prism (Kitamura *et al.*, 2001), available time for activity participation (Fransen *et al.*, 2018a; Landau *et al.*, 1981) and Burns-Miller measure (Ding *et al.*, 2016). Lavieri *et al.* (2018) further tested the influence of virtual accessibility on the level of participation in face-to-face activities.

Regarding the type of activities and purpose of the trips analysed by the literature, the most frequent type is discretionary trips/activities, such as shopping and maintenance. Most of these studies justify the focus on discretionary trips/activities by arguing that individuals have a relatively inelastic demand for work trips/activities on a day-to-day basis.

Despite this, some studies assessed the relationship between accessibility and mandatory (work and education) trips/activities. Some other papers did not differentiate between trip purpose or activity type, adopting only a general category for all activities. Regarding the modes of transport used in the analyses, the most frequent is the auto, followed by public transport, walking and cycling. Lavieri *et al.* (2018) considered virtual access to activities. Some studies did not differentiate between the transport mode used to access activities.

Various methods have been employed to test the relationship between levels of accessibility and levels of participation in activities or the number of trips made. The most commonly used method to test the relationship under study was multivariate linear regression (Cordera *et al.*, 2017; Ding *et al.*, 2016; Hanson and Schwab, 1987; Kitamura *et al.*, 1997; Kröger *et al.*, 2018; Leake and Huzayyin, 1980; Næss, 2006; Purvis *et al.*, 1996; Robinson and Vickerman, 1976; Seo *et al.*, 2013; Vickerman, 1974; Wu *et al.*, 2012), followed by generalised linear models such as logistic regression (Ding *et al.*, 2016; Kröger *et al.*, 2018; Lee and Goulias, 1997; Zhang, 2005), Poisson regression (Cordera *et al.*, 2017; Thill and Kim, 2005), negative binomial regression (Allen and Farber, 2020; Merlin, 2015; Zhang *et al.*, 2019), and zero-inflated negative binomial regression (Fransen *et al.*, 2018a; Tian and Ewing, 2017). Other methods found in the literature include ANOVA (Ewing *et al.*, 1996; Handy, 1996; Masoumi, 2021; Wermuth, 1982; Williams, 1989), structural equation modelling (Cheng *et al.*, 2019; Golob, 2000; Lavieri *et al.*, 2018; Schwanen *et al.*, 2007), linear probability model (Landau *et al.*, 1981), Pearson correlation coefficient (Handy, 1993; Kitamura *et al.*, 2001; Williams, 1989), Multiple Discrete Continuous Extreme Value (MDCEV) (Bhat *et al.*, 2013), weighted least squares (Masoumi, 2021), propensity match score Wang and Cao (2017), basic descriptive statistics (Downes and Morrell, 1981; Handy, 1996; Koenig, 1980), and interviews (Næss, 2006). Only two papers applied spatial regression models (Calvo *et al.*, 2019; Cordera *et al.*, 2017).

Although we might expect higher accessibility levels to be associated with a greater number of trips and more activity participation from the theoretical point of view, the empirical results do not indicate a consensus regarding the validity of this statement. Some articles found that accessibility levels are associated with higher trip making and activity participation (Allen and Farber, 2018; Calvo *et al.*, 2019; Ding *et al.*, 2016; Golob, 2000; Handy, 1996; Koenig, 1980; Krasić and Novačko, 2015; Leake and Huzayyin, 1980; Lee and Goulias, 1997; Merlin, 2015; Purvis *et al.*, 1996; Robinson and Vickerman, 1976; Tian and Ewing, 2017), while other studies found that this relationship is weak (Hanson and Schwab, 1987; Kitamura *et al.*, 1997) or not statistically significant (Downes and Morrell, 1981; Ewing *et al.*, 1996; Handy, 1993; Wang and Cao, 2017; Wermuth, 1982).

The studies that found no significant or weak effect were published before 1996 (except for Wang and Cao (2017)) . It means that they used methods and data less sophisticated than the more re-cent papers. They all adopted place-based accessibility measures (gravity-type, distance to CBD, minimum distance to transport or activity, household density, and area characteristics), and only one looked at the relationship between accessibility and activity participation (Wermuth, 1982). However, Wermuth (1982) applied our sample's less robust accessibility measure, location characteristics, as a control variable in the ANOVA. The other five works were focused on trip making.

Some papers found mixed effects (Bhat *et al.*, 2013; Cheng *et al.*, 2019; Cordera *et al.*, 2017; Fransen *et al.*, 2018a; Kitamura *et al.*, 2001; Kröger *et al.*, 2018; Landau *et al.*, 1981; Masoumi, 2021; Næss, 2006; Schwanen *et al.*, 2007; Seo *et al.*, 2013; Thill and Kim, 2005; Zhang, 2005; Zhang *et al.*, 2019). For example, Cordera *et al.* (2017) found that the validity of the relationship varies according to the mode of transport. While greater accessibility is associated with a decrease in the number of trips to work by private vehicles, they also found that it is associated with an increase in public transport trips. Cheng *et al.* (2019) found that population density significantly affects trip generation, but employment density does not. On the other hand, population and employment density variables show insignificant impacts on activity participation. Kröger *et al.* (2018) found that accessibility to the nearest business district positively impacts home-based shopping trips but not home-based work trips. Schwanen *et al.* (2007) suggest that in a neighbourhood with good accessibility to shops, men may take care of more household tasks due to fewer space-time constraints. However, they also found that as the travel time to the nearest shopping centre for clothing or footwear rises, individuals participate more frequently in shopping for convenience goods independent of their spouse.

Kitamura *et al.* (2001) notice that the size of the space-time prism is the critical determinant of activity participation but not the number of opportunities within the prism. On the one hand, Fransen *et al.* (2018a) findings indicate a moderate positive correlation between the available time to activity participation and partaking in discretionary activities. On the other hand, the findings indicate that the gravity-type measure shows a negative and highly significant relationship to activity participation. Seo *et al.* (2013) found that maintenance trips are negatively associated with accessibility levels, while other purpose trips are positively associated. Thill and Kim (2005) tested 72 variations of accessibility measures and found that half of the statistically significant accessibility variables revealed a positive relationship with the trip making, while the other half indicated a negative relationship. According to Zhang *et al.* (2019)'s findings, people who live in denser neighbourhoods are more likely to make more home-based work and shopping trips; however, household density negatively impacts entertain-ment or social activities. Næss (2006)'s results indicate that individuals who live in the more peripheral residential area tend to make 1.5 more daily trips than their peers living in the area closer to the Copenhagen CBD. At the same time, better accessibility is associated with more activity participation. Landau *et al.* (1982) found that time constraints were significant in the leisure trip models and not significant in the maintenance trips models. The number of employees in commerce and services in residential areas positively influences the number of maintenance trips but negatively influences leisure trip making.

Finally, a group of studies found a negative relationship between accessibility and activity participation or trip making (Lavieri *et al.*, 2018; Williams, 1989; Wu *et al.*, 2012). Williams (1989) found that activity participation reduces as accessibility increases and that there is no association between the number of trips made and the accessibility conditions. Although Wu *et al.* (2012) and Lavieri *et al.* (2018) found a negative relationship, their findings are reasonable according to the theoretical literature. Wu *et al.* (2012) findings indicate that higher levels of walking and public transport accessibility are associated with fewer trips by car, which make sense. Lavieri *et al.* (2018) findings indicate that virtual accessibility negatively impacts the number of physical maintenance activities. However, Lavieri *et al.* (2018) also found that physical accessibility negatively impacts the number of maintenance activities and that individuals who perceive ease of access to opportunities tend to concentrate their maintenance activities in fewer and longer episodes. Table 4.1 summarises the studies reviewed in this section.

Table 4.1: Summary of findings of studies about the relationship between accessibility and activity participation and trip making.

Study	Study Area	Accessibility Measure	Method	Study focus	Trip / Activity Purpose	Transport Mode	Findings
(Vickerman, 1974)	Oxford, United Kingdom	Location-based (Gravity-type)	Multivariate linear regression (MLR)	Trip making	Shopping; Leisure	All travel modes, Auto, Public transport and Walk	Positive effect. The cost component of accessibility measure positively impacts shopping trips, while the attraction component has a dominant influence on leisure trips.
Robinson and Vickerman (1976)	Sussex, United Kingdom	Location-based (Gravity-type)	Multivariate linear regression (MLR)	Trip making	Shopping	Auto and Public transport	Positive effect. The availability of shopping locations in a given area and their transport characteristics positively influence shopping activity.
Koenig (1980)	Lemans, Marseilles, Rouen, Nice, Grenoble - France	Utility-based	Basic descriptive statistics	Trip making	Work	Auto and Public transport	Positive effect. Accessibility is a powerful determinant of trip rate.
Leake and Huzayyin (1980)	Middlesbrough, United Kingdom	Location-based (Minimum distance; Minimum time) and Infrastructure-based (Headway; Transport Network structure)	Multivariate linear regression (MLR)	Trip making	Work; Education; Others; General	All travel modes, Auto and Public transport	Positive effect. The most affected trip types were public transport trips followed by "all mode" trips. The more negligible impact was for trips by private transport. The most significant effect by trip purpose was on home-based other trips, regardless of travel mode.
Downes and Morrell (1981)	Reading, United Kingdom	Location-based (Distance to CBD)	Descriptive statistics	Trip making	General	Auto, Public transport, Bicycle and Walk	No significant effect. Household locations do not affect the aggregate trip frequency by all modes.
Landau *et al.* (1981)	Tel-Aviv, Israel	Spatial-temporal (Possible activity duration) and Location-based (Container-type)	Linear probability model (LPM)	Trip making	Maintenance; Leisure	Auto and Public transport	Mixed effect. Time constraints were significant in the leisure trip models and not significant in the maintenance trips models. The number of employees in commerce and services in residential areas positively influences the number of maintenance trips but negatively influences leisure trip making.

Table 4.1: Summary of findings of studies about the relationship between accessibility and activity participation and trip making.

Study	Study Area	Accessibility Measure	Method	Study focus	Trip / Activity Purpose	Transport Mode	Findings
Wermuth (1982)	Rhine-Neckar (Germany) and Salzburg (Austria)	Location-based (Area characteristics)	Nested ANOVA	Activity participation	Work; Education; Shopping; Leisure; Others	All travel modes	No significant effect. The accessibility to central facilities and the characteristics of the residential neighbourhood is negligible.
Hanson and Schwab (1987)	Uppsala, Sweeden	Location-based (Gravity-type)	Multivariate linear regression (MLR)	Trip making	Discretionary (Non-work; Shopping; Social)	Auto, Walk and Bicycle	Weak effect. The relationship between accessibility and the number of discretionary trips is statistically significant only for men. The correlation coefficients are not very expressive.
Williams (1989)	Hamilton, Canada	Location-based (Gravity-type)	Pearson correlation coefficient and ANOVA	Trip making and Activity participation	General	Auto	Negative effect. The activity participation reduces as accessibility increases. No association was found between the number of trips made and the accessibility conditions.
Handy (1993)	San Francisco Bay Area, United States	Location-based (Gravity-type)	Pearson correlation coefficient	Trip making	Shopping	Auto	No significant effect. The relationship between regional accessibility and shopping trips was practically non-existent, as was the relationship between local accessibility and shopping trips.
Ewing *et al.* (1996)	Palm Beach and Dade counties, Florida, United States	Location-based (Gravity-type)	ANOVA	Trip making	Mandatory (Work) and Discretionary (Shopping; Social; Recreation; Others)	Auto, Walk and Bicycle	No significant effect. Accessibility seems to have negligible effects on home-based trip generation.
Handy (1996)	San Francisco Bay Area, United States	Location-based (Cumulative Opportunities; Weighted time; Minimum time)	Descriptive data analysis and ANOVA	Trip making	Discretionary (Shopping; Supermarket; Having Meal)	Auto and Walk	Positive effect. Greater accessibility, both in terms of short distances and a greater variety of potential destinations, is associated with higher trip frequencies to convenience stores and regional trips to shopping centres.

Table 4.1: Summary of findings of studies about the relationship between accessibility and activity participation and trip making.

Study	Study Area	Accessibility Measure	Method	Study focus	Trip / Activity Purpose	Transport Mode	Findings
Purvis *et al.* (1996)	San Franciso Bay Area, United States	Location-based (Minimum time)	Multivariate linear regression (MLR)	Trip making	Shopping; Leisure	Auto, Walk and Bicycle	Positive effect. There is an inverse relationship between work trip duration and trip frequency for reasons other than work.
Lee and Goulias (1997)	Centre County, Pennsylvania, United States	Location-based (Minimum distance; Minimum time; Distance sum; Weighted distance; gravity-based)	Logit	Trip making	Shopping	Auto	Positive effect. The shortest path (minimum distance) measure and the gravity-type with a Gaussian deterrence function accessibility measure are the ones that best explain travel behaviour.
Kitamura *et al.* (1997)	San Franciso Bay Area, United States	Location-based (Minimum distance to transport; Minimum distance; Household Density)	Multivariate linear regression (MLR)	Trip making	General	Public transport, Walk and Bicycle	Partial effect. The number of public transport trips increases with better accessibility to railway stations and is associated with residential density. The presence of sidewalks is positively associated with the number of non-motorized trips.
Golob (2000)	Portland, Oregon, United States	Location-based (Cumulative Opportunities) and Utility-based	Structural Equation Modelling (SEM)	Activity participation	Work, Maintenance and Discretionary (Leisure)	All travel modes	Positive effect. Accessibility levels are positively related to participation in out-of-home non-work activities, simple home-based trip chains for non-work purposes, and negatively related to work travel time.
Kitamura *et al.* (2001)	Kyoto-Osaka-Kobe Metropolitan Area, Japan, and Southern California, United States	Location-based (Gravity-type) and Spatio-temporal (Number of activities in the Space-time Prism; Volume of Space-time Prism)	Pearson correlation coefficient and Structural equation modelling (SEM)	Trip making and Activity participation	Shopping and Leisure	Auto and Public transport	Mixed effect. The size of the space-time prism, not the number of opportunities it contains, is the critical determinant of activity participation. Time availability is more influential than the opportunities distribution in activity participation and trip making (Japan).

Table 4.1: Summary of findings of studies about the relationship between accessibility and activity participation and trip making.

Study	Study Area	Accessibility Measure	Method	Study focus	Trip / Activity Purpose	Transport Mode	Findings
Thill and Kim (2005)	Minneapolis-St. Paul, Minnesota, United States	Location-based (Gravity-type; Cumulative Opportunities)	Poisson Regression	Trip making	Work; Shopping; Education and Others	Auto	Mixed effect. Half of the statistically significant accessibility variables revealed a positive relationship with the trip making. The other half indicated a negative relationship. The combined effect of significant accessibility measures on travel demand is complex and non-linear.
Zhang (2005)	Boston, United States	Location-based (Gravity-type)	Logit Regression	Activity Participation	Non-work (school, shopping, social, personal, pick up/drop off and other)	Auto and Public Transport	Mixed effect. Accessibility was positive, statistically significant to activity–travel frequency for school and social activities. Increase in accessibility was associated with lower odds of making additional shopping trips.
Næss (2006)	Copenhagen Metropolitan Region, Denmark	Location-based (Distance to CBD)	Interviews and multivariate linear regression (MLR)	Trip making and Activity participation	Leisure; Maintenance; Visiting friends and Work	Auto, Public transport, Walk and Bicycle	Mixed effect. The results indicate that respondents from the more peripheral residential area tend to make 1.5 more daily trips than their peers living in the area closer to the Copenhagen CBD. At the same time, better accessibility is associated with more activity participation.

Table 4.1: Summary of findings of studies about the relationship between accessibility and activity participation and trip making.

Study	Study Area	Accessibility Measure	Method	Study focus	Trip / Activity Purpose	Transport Mode	Findings
Schwanen *et al.* (2007)	Amsterdam - Utretcht, Netherlands	Location-based (Cumulative Opportunities; Minimum time to transport)	Structural Equation Modelling (SEM)	Trip making and Activity participation	General; Shopping; Personal Business and Others	Auto	Mixed effect. Accessibility positively influences between-partner interactions in maintenance activity participation. They suggest that in a neighbourhood with good accessibility to shops, men may take care of more household tasks due to fewer space-time constraints. The travel time to the nearest shopping centre for clothing or footwear suggest that individuals participate more frequently in shopping for convenience goods independent of their spouse, as the travel time rises.
Wu *et al.* (2012)	San Francisco, United States	Mix of location-based with Infrastructure-based (Distance to Transport and Headway).	Multivariate linear regression (MLR)	Trip making	General	Auto	Negative effect. Higher levels of walking and public transport accessibility are associated with fewer trips by car.
Bhat *et al.* (2013)	Los Angeles Region, United States	Location-based (Cumulative Opportunities; Gravity-type)	Multiple Discrete Continuous Extreme Value (MDCEV)	Activity Participation	Maintenance (shopping, non-shopping, social, entertainment, visiting friends and family, active recreation, eat-out, work-related)	Auto	Mixed effects.

Table 4.1: Summary of findings of studies about the relationship between accessibility and activity participation and trip making.

Study	Study Area	Accessibility Measure	Method	Study focus	Trip / Activity Purpose	Transport Mode	Findings
Seo *et al.* (2013)	Seoul, South Korea	Utility-based (Logsum) and Infrastructure-based	Multivariate linear regression (MLR)	Trip making	Shopping, personal business and leisure	Auto and Public transport	Mixed effect. Maintenance trips are negatively related to accessibility, while other purpose trips are positively related. Higher accessibility does not always lead to more activity participation.
Krasić and Novačko (2015)	Zagreb, Croatia	Location-based (Distance to transport)	Multivariate linear regression (MLR)	Trip making	General	Auto and Public transport	Positive effect
Merlin (2015)	United States	Location-based (Residential and employment density)	Negative Binomial Regression (NB)	Activity Participation	Non-work activities	All travel modes	Positive effect. Greater residential and employment densities have a sizeable effect on levels of household non-work activity, with the most significant influence on households with the fewest vehicles.
Ding *et al.* (2016)	Beijing, China	Space-time (Aggregated utility of opportunities)	Logit and Linear Regression	Activity Participation	Shopping	Auto	Positive effect. Greater person-based accessibility has positive effects on the frequency and duration of shopping activity participation.
Cordera *et al.* (2017)	Santander, Spain	Location-based (Gravity-type; Time to CBD)	Multivariate linear regression (MLR), Spatial autoregressive models (SAR), Spatial autoregressive models in the error term (SEM), and Spatially filtered Poisson regression Models (SPO)	Trip making	Work, Study, Others (Non-discretionary)	Auto, Motorcycle and Public transport	Mixed effect. More accessibility to opportunities decreases trip making in private vehicles for work purposes, whereas it increases trip production in other transport modes for non—mandatory purposes.
Tian and Ewing (2017)	Portland, Oregon, United States	Location-based (Cumulative Opportunities; Distance to transport)	Zero-Inflated Negative Binomial Regression (ZINB)	Trip making	General	Walk	Positive effect. transport stop density and employment accessibility are good predictors of the number of walk trips.
Wang and Cao (2017)	Hong Kong, China	Location-based (Gravity-type)	Propensity Score Match	Trip making	General	All travel modes	No effect

Table 4.1: Summary of findings of studies about the relationship between accessibility and activity participation and trip making.

Study	Study Area	Accessibility Measure	Method	Study focus	Trip / Activity Purpose	Transport Mode	Findings
Fransen *et al.* (2018a)	Wasatch Front region, Utah, United States	Spatial-temporal (Possible activity duration) and Location-based (Gravity-type)	Zero-Inflated Negative Binomial Regression (ZINB)	Activity Participation	Discretionary (Exercise, Having a Meal, Personal Business, Religious, Shopping, Social, Leisure, Others)	Auto	Mixed effect. There is a moderate positive correlation between the spatial-temporal accessibility measure and participants' surveyed partaking in discretionary activities. The gravity-type measure shows a negative and highly significant relationship to activity participation.
Kröger *et al.* (2018)	Germany	Location-based (Minimum time)	Linear regression and Logit	Trip making	Mandatory (Work) and Discretionary (Shopping)	Auto	Mixed effect. Accessibility to the nearest business district positively impacts home-based shopping trips but not home-based work trips.
Lavieri *et al.* (2018)	Great Britain	Virtual Accessibility and Location-based (Minimum time)	Structural Equation Modelling (SEM)	Activity Participation	Mandatory (Work), Maintenance, Discretionary	Virtual	Negative effect. Virtual accessibility reduces both the number and the duration of work episodes. Virtual accessibility negatively impacts the number of maintenance activities but does not seem to affect the duration of out-of-home maintenance activities. Physical accessibility negatively impacts the number of maintenance activities. Individuals who perceive ease of access to opportunities tend to concentrate their maintenance activities in fewer and longer episodes
Calvo *et al.* (2019)	Madrid, Spain	Location-based (Job density; Container-type)	Geographically Weighted Regression (GWR)	Trip making	General	Metro	Positive effect. The number of daily trips increases with the increase of job density. The accessibility measure that accounts for the number of residents at less than 600 m to a metro station is statistically significant only for suburban zones.

Table 4.1: Summary of findings of studies about the relationship between accessibility and activity participation and trip making.

Study	Study Area	Accessibility Measure	Method	Study focus	Trip / Activity Purpose	Transport Mode	Findings
Cheng *et al.* (2019)	Nanjing, China	Location-based (Jobs density; Population density)	Structural Equation Modelling (SEM)	Trip making and Activity participation	Mandatory (Work, Education or Bureaucracy), Maintenance (Shopping, Visiting friends, Seeing a doctor), and Discretionary	Auto, Motorcycle, Walk, Public , Bicycle	Mixed effect for trip making. Population density significantly affects trip generation, and the employment density variable does not indicate any substantial effects on trip generation. No significant effect on activity participation. Population and employment density variables show insignificant impacts on activity participation.
Zhang *et al.* (2019)	Portland, Oregon, United States	Location-based (Household density and Container measure)	Negative Binomial Regression (NB)	Trip making	General, Mandatory(Work, Education), shopping, recreation, and Other	All travel modes	Mixed effect for trip making. People who live in denser neighbourhoods are more likely to make more trips. Workers who live in denser areas are likely to generate more home-based work trips. Higher urban living infrastructure density is associated with more shopping trips. Household density has a negative impact on entertainment or social activities.
Allen and Farber (2020)	Greater Toronto and Hamilton Area, Canada	Location-based (Gravity)	Negative Binomial Regression (NB)	Activity Participation	General	All travel modes	Improvements in accessibility by public transport are associated with people participating in a greater number of daily activities. Accessibility and activity participation presents a sigmoidal relationship.
Masoumi (2021)	(Cairo, Istanbul, Tehran), Middle East and North Africa	Location-based (Container measure, Distance to activities)	ANOVA and Weighted Least Squares	Trip-making	Mandatory (work and study) and non-work	All travel modes	Mixed effect. Higher value of accessibility measured by container measure is associated with less mandatory trips. Shorter distance to activities is associated with more mandatory trips.

Some conclusions can be drawn from the empirical evidence on the relationship between accessibility and activity participation or trip making. First, there is no consensus whether greater levels of accessibility lead to greater activity participation or more trip taking. No clear pattern was found in the findings of reviewed articles. There are divergent findings between papers that use the same accessibility measures, the same statistical methods, the same study focus, the same activity or trip purpose and the same transport mode. Second, very few studies have been devoted to studying this relationship from TRSE and transport equity perspectives. Because of that, many studies that focused on trip generation used accessibility measures aggregated by zones and failed to control for people's interpersonal heterogeneity adequately. Many of the studies reviewed and the TRSE literature, in general, point out that individual characteristics play an essential role in an individual's chances of participation.

Third, most studies focus on Global North contexts, and empirical evidence is scarce for Global South contexts. Fourth, given the variability of the findings, one of the hypotheses to be raised is that this relationship is context-specif. Fifth, despite the large number of studies reviewed, none of them used identification strategies that inferred a causal relationship between accessibility and activity participation in or trip making. All studies that we found on the subject are merely correlational. One may argue that structural equation modelling (SEM) can account for the causal relationships between the variables included in the model. However, Bollen and Pearl (2013), in their paper entitled "Eight myths about causality and structural equation models", argue that "developers and users of SEMs are under the mistaken impression that SEMs can convert associations and partial associations among observed and/or latent variables into causal relations." (Bollen and Pearl, 2013, p.308). For a more in-depth discussion, see Bollen and Pearl (2013).

Theoretical Discussion

The body of empirical evidence indicates that the mathematical relationship between accessibility and participation in activities is understudied. However, understanding the shape of this relationship is essential for determining whether, where, and to what extent accessibility improvements would increase activity participation (Allen and Farber, 2020). Most studies about the topic assume a linear relationship between accessibility and activity participation (black line in Figure 4.1). (Martens, 2006, 2016a), otherwise, suggest that at an extremely low level of accessibility, an individual's activity participation will be severely restricted. At any level beyond the absolute minimum, it is expected that the individual will be able to participate at least in some activities. For any given level beyond the absolute minimum, people will differ in their level of activity participation, with some individuals with higher levels and others with lower levels of participation. However, it is expected that the average level of participation in activities of all people with a particular level of accessibility will increase with an increase in accessibility (Luz and Portugal, 2021; Martens, 2016a). Due to diminishing marginal gains from accessibility variation, the relationship is expected to be concave (blue line in Figure 4.1). It means that the impact of one additional "unit" of accessibility will have a greater impact at lower levels than at higher levels of accessibility. Martens (2016a) also argues that at higher levels of accessibility, a substantial variation in the level of activity participation is expected due to people's preferences and other factors.

Allen and Farber (2020) expanded the theory proposed by Martens (2016a) and argued that the relationship between accessibility and activity participation has a sigmoidal shape (orange line in Figure 4.1). Their argument suggests that at very low levels of accessibility, the curve will be flatter since moving from very low to low levels of accessibility may only have a minor effect as low levels of accessibility will still be insufficient in enabling participation in many daily activities (Allen and Farber, 2020). Allen and Farber (2020) empirical findings are consistent with their argument. The other reviewed study that discussed the mathematical relationship between accessibility and activity participation was Fransen *et al.* (2018a), which found a curve with a shape similar to the green line in Figure 4.1. As they modelled the relationship using a negative binomial regression, activity participation level exponentially increases when accessibility increases and the model failed to capture the diminishing effect on participation for the highest levels of accessibility. This hypothesis does not align with the Martens (2016a) proposition, nor completely with Allen and Farber (2020). However, we can speculate that Fransen *et al.* (2018a)'s curve shape depicts the low side of the accessibility spectrum of the Allen and Farber (2020)'s sigmoid curve.

Much of the TRSE research treat accessibility as a critical indicator for the number

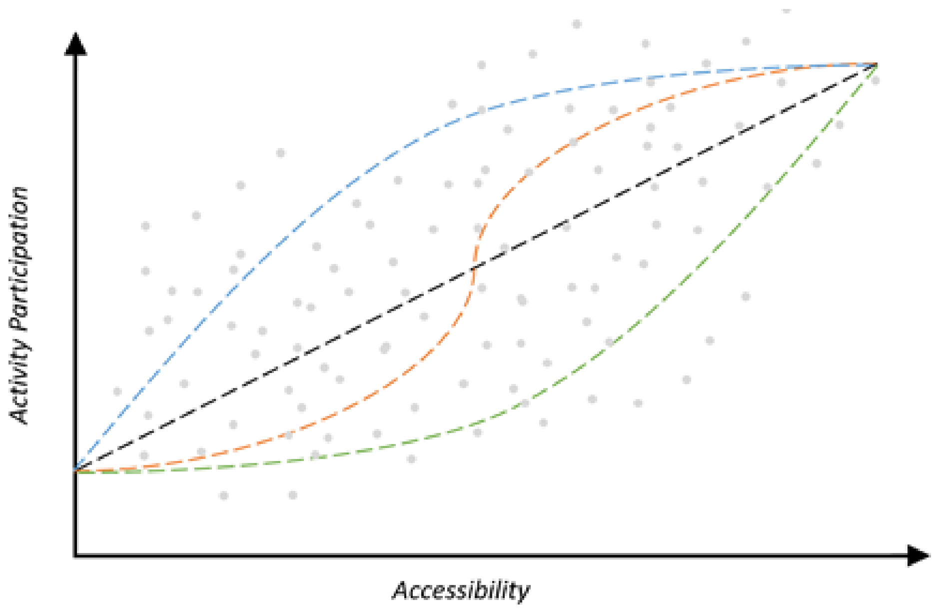


Figure 4.1: Theoretical relationships between accessibility and activity participation

Source: Adapted from Allen and Farber (2020)

of opportunities available to individuals. From a theoretical perspective, such a statement makes complete sense. However, previous studies investigating the accessibility-participation relationship were inconclusive, indicating that increasing accessibility has a limited impact on activity participation levels if any (Fransen *et al.*, 2018a; Martens, 2016a). It may suggest that the link between accessibility and activity participation is less direct than expected. In this sense, evaluating policy interventions in terms of accessibility may lead to a substantial overestimation of the possible impacts on activity participation (Martens, 2016a) and, therefore, on social inclusion. Also, the relationship between accessibility and activity participation was understudied in Global South contexts and from the TRSE and transport equity perspectives. Most of the reviewed studies tend to use aggregate approaches and fail to adequately control for interpersonal characteristics when testing the accessibility-activity participation relationship. Finally, previous studies were merely correlational and did not infer causality between accessibility and activity participation.

This paper focuses explicitly on inferring a causal relationship between accessibility levels and activity participation in a Global South context. The study focuses on the social consequences of activity participation rather than the implications of particular travel demand. In this sense, we do not differentiate by transport mode the activities accessed by individuals. We assessed the accessibility-activity participation relationship according to the type of activities accessed, mandatory activities (work and education), discretionary activities (leisure, shopping or having a meal), and total activities (without distinguishing between purpose). We decided to use the cumulative opportunities accessibility measure due to its simplicity, ease of interpretation and because it is the accessibility measure most used in practice by policymakers (Boisjoly and El-Geneidy, 2017b). Aspects such as ease of operationalisation and interpretation of the accessibility measure are crucial to it be used by planners, especially in a Global South context, where transport agencies face data limitations and have low skilled technical staff (Barboza *et al.*, 2021). Another aspect distinguishing our study from past works that used place-based measures is disaggregation. We analysed the accessibility-activity participation relationship considering each individual's accessibility level and personal characteristics. The following section presents the study area, the data and details about the accessibility measure adopted.

4.3 Study Area, Accessibility Measure and Data

4.3.1 Study Area

The study is situated in the City of São Paulo, Brazil, Latin America's largest city and home to more than 12 million people. São Paulo's development illustrated Brazil's fast urbanisation process throughout the last century when the city had average annual growth rates of more than 4,5 per cent until 1950 (Moreno-Monroy and Ramos, 2020). Following the 1950s, the city had its most significant development driven by the placement of industrial parks, leading to an ongoing spatial reconfiguration closely linked to a traditional monocentric pattern (Moreno-Monroy and Ramos, 2020). In the following decades, the unmanaged centrifugal expansion developed a wide suburban outer belt filled by the poor and less educated population (Moreno-Monroy and Ramos, 2020). Consequently, the locations with lower levels of job accessibility are also those with poorer socioeconomic status, shorter life expectancies and disproportionally precarious infrastructure (Slovic *et al.*, 2019).

Due to uncontrolled urban expansion, the historical prioritisation of private over collective modes of transport, and a suboptimal and uneven provision of urban public transport, a considerable share of the more disadvantaged population faces low accessibility levels and, therefore, longer commuting times and distances (Biderman, 2008; Boisjoly *et al.*, 2020; Slovic *et al.*, 2019). The weaker transport connectivity in regions farther from the wealthier central areas and the concentration of jobs in the CBD prevent carless workers from accessing potential employers far from the focal points of public transport accessibility(Boisjoly *et al.*, 2017; Haddad and Barufi, 2017). As a result, access to opportunities is constrained for this population group, making São Paulo much more unequal than Global North cities (Giannotti *et al.*, 2021).

The 2017 São Paulo OD Survey estimates that 42 million trips are made daily in the Metropolitan Region of São Paulo, 67% in motorised vehicles and 33% in non-motorised modes (Companhia do Metropolitano de São Paulo – Metrô, 2019). Among the motorised trips, approximately 54% occurs in collective modes, while 46% are made in private vehicles. When evaluated by income bracket, 72% of families' trips with incomes up to R$1,908 (approximately U$ 598) occur by public transport, while in the highest income group (above R$1,448) (approximately U$ 454), only 20% are made by public transport (Companhia do Metropolitano de São Paulo – Metrô, 2019). This statistic suggests a high public transport dependency among low-income households.

The metro network in the city of São Paulo is composed of 6 lines, totalling 101.1 km in length and 89 stations. In 2017, the metro network reached the mark of 1.3 billion passengers transported, standing out as one of the most productive in the world in terms of passenger per kilometre and passenger per car-km. Despite its high productivity, the metro mode share only accounts for 12% of motorised trips, a low proportion compared to other metropolitan areas of similar size. The metro is complemented by a 273-km suburban railway and one of the most extensive municipal bus systems globally, accounting for a fleet of 14500 buses that runs 3 million km on weekdays. The railway and bus system is responsible for 4.4% and 29.4% of motorised trips, respectively, in the metropolitan region. The city also has 684 km of bikeways, 500 km of bus-only lanes on existing roadways, and 131.2 km of bus corridors. Figure 2 presents the transport infrastructure of medium and high capacity modes in the city of São Paulo.

4.3.2 Accessibility Measure

The accessibility data used in this study was extracted from the Access to Opportunities Project (AOP) of the Institute for Applied Economic Research (IPEA) (Pereira *et al.*, 2019). The objective of AOP is to understand the conditions of transportation and inequalities of access to opportunities in Brazilian cities. The AOP estimates the population's access to work opportunities, health services and education by mode of transport in the largest urban regions in Brazil annually. Such estimates are made using GTFS (General Transit Feed Specification) data on public transport provided by the municipalities, data on the road network for September 2019 from the Open Street Map website, data from the 2010 Demographic Census of the Brazilian Institute of Statistical Geography (IBGE) and data on formal employment from the 2017 Annual Social Information Report (RAIS) of the Ministry of Labour.

Job accessibility variables by public transport were selected from the AOP database. Accessibility levels were measured using the cumulative opportunity measure (CUM) and depict the proportion of formal jobs in the municipality accessed by public transport within a given travel time threshold. Computed travel times were calculated during peak hours and included walking to and from stops, waiting for a public transport vehicle, time spent travelling in a public transport vehicle, and any time spent transferring between vehicles. Four time thresholds were tested 30, 60, 90 and 120 minutes. The accessibility values calculated by the AOP have a high spatial resolution, with values aggregated in H3 hexagons at resolution 9, developed by technology company Uber. More specifically, the values are aggregated in hexagons of 174.38 meters side.

The CUM measure is defined as follows:

$$CUM = \frac{\sum_j a_j \ddot{h}_\delta\left(t_{ij}\right)}{N} \qquad \delta > 0 \tag{4.1}$$

Where a_j is the number of jobs in j, δ is time threshold (30, 60, 90 or 120 minutes), c_{ij} the travel time between individual's location (i) and location j, and e $h_\delta\left(c_{ij}\right)$ assumes the value one if $c_{ij} \leq \ \delta$ and 0 if $c_{ij} > \delta$, and N is the total number of formal jobs in the São Paulo municipality. Allen and Farber (2020) and Cordera *et al.* (2017) pointed out that employment distributions are theorised to be a proxy for many other types of potential destinations (e.g., services, shopping, informal jobs, etc.). Thus, the accessibility values used are reasonable estimates of the level of accessibility to general activities in the city.

There are some theoretical and practical reasons to use CUM measure in this study. From a theoretical point of view, CUM considers the disutility in time cost that individual faces and is sensitive to variations in the quantity and spatial distribution of activities. It does not make assumptions regarding individuals' perceptions about the quality of opportunities or how they perceive transportation costs. CUM accounts for all the possibilities of participation open to individuals and are not calculated based on observed travel behaviour, which is an essential feature from the TRSE perspective since people are interested not only in the activities they achieve but also in the range of activities they could potentially achieve (Luz and Portugal, 2021; Martens, 2016b; van Wee, 2016; van Wee and Geurs, 2011). The value of the option chosen will depend not only on the characteristics of that option but also on the available range of options (Luz and Portugal, 2021; Martens, 2016b; van Wee, 2016).

CUM also has the advantage to do not suffering from the "expensive taste" and "adaptive preferences" issues faced by utility measures (see Martens (2016b), Martens and Golub (2012) and Ryan and Pereira (2021)), which may distort accessibility distribution among the population. Also, CUM permits using a point in space as the analysis unit and thus avoids spatial aggregation biases. It is crucial since, from the TRSE perspective, accessibility is a fundamentally individual phenomenon (Miller, 2006) and not always spatially clustered (Hine and Grieco, 2003). Although we attribute the accessibility value from a spatial unit to the individual, the bias generated by that is small due to the extremely high spatial resolution.

From a practical perspective, CUM is unanimous among researchers in ease of interpretation and communication (Curl *et al.*, 2011; Geurs and van Wee, 2004; Koenig, 1980; Neutens, 2015; Neutens *et al.*, 2010). It is one of the most used accessibility measures in practice (Boisjoly and El-Geneidy, 2017b). CUM requires only information regarding opportunities' quantity and spatial distribution, and travel time from the reference location to these opportunities. It does not require data regarding the attractiveness of the activities and does not require the adoption of a transport deterrence function with a calibrated parameter. In addition, the computational power demanded to calculate CUM is considerably lower than other more realistic measures, allowing the application at the macro scale, such as entire cities and metropolitan regions. Due to the less powerful equipment requirements, CUM is much easier to implement by technicians in transportation planning agencies and interpreted by policymakers and the population, which is crucial in the Global South context, where most transport agencies face data limitations and have low skilled technical staff (Barboza *et al.*, 2021). Policymakers, researchers, and the public will not face difficulties understanding the results of these measures.

4.3.3 Data

The data used in this research come from different databases, such as the 2017 Origin and Destination (OD) Survey of the São Paulo Metropolitan Region (Companhia do Metropolitano de São Paulo – Metrô, 2019); Access to Opportunities Project (AOP) (Pereira *et al.*, 2019); 2010 Demographic Census of the Brazilian Institute of Statistical Geography (Instituto Brasileirode Geografia e Estatística - IBGE, 2011); and the 2010 Paulista Social Vulnerability Index (Fundação Sistema Estadual de Análise de Dados, 2013).

Data on individuals' activities were taken from the 2017 RMSP Origin and Destination (OD) Survey. The OD survey collects information regarding daily commuting within the Metropolitan Region of São Paulo and sociodemographic data from households, families, and individuals. The OD Survey data is collected from households chosen through sampling, in which all individuals answer a questionnaire about their sociodemographic information and trips made on the weekday prior to the OD Survey taker's visit. The data of the 2017 OD Survey were collected between June 2017 and October 2018, except for the school holidays periods, considered atypical for conducting the survey.

Disaggregated data at the individual level were extracted from the OD 2017 Survey database exclusively for the São Paulo municipality. The choice to conduct the research only within the municipality of São Paulo is justified by the unavailability of accessibility data for the entire metropolitan region. Among the selected variables are age, gender, study status, level of education, employment status, number of family members, individual income, and family situation. Individuals aged 13 or younger were removed from the dataset because of their dependence on other family members to travel and, therefore, participate in activities. New variables were generated from the original database by dividing the number of private vehicles (cars and motorcycles) and family income by the number of people in the family.

Variables regarding the number of activities the individual participated in were created from the travel diary. Trips to destinations other than home were considered an activity in the "total activities" category, trips for work or study purpose to destinations other than home were considered a mandatory activity, and trips for discretionary purposes (leisure, shopping or having a meal) to destinations other than home were counted as a discretionary activity (Figure 4.2). It is important to note that the sum of discretionary activities and mandatory activities does not equal the number of total activities. Some categories, such as travel for health purposes, were only included in the total activities category.

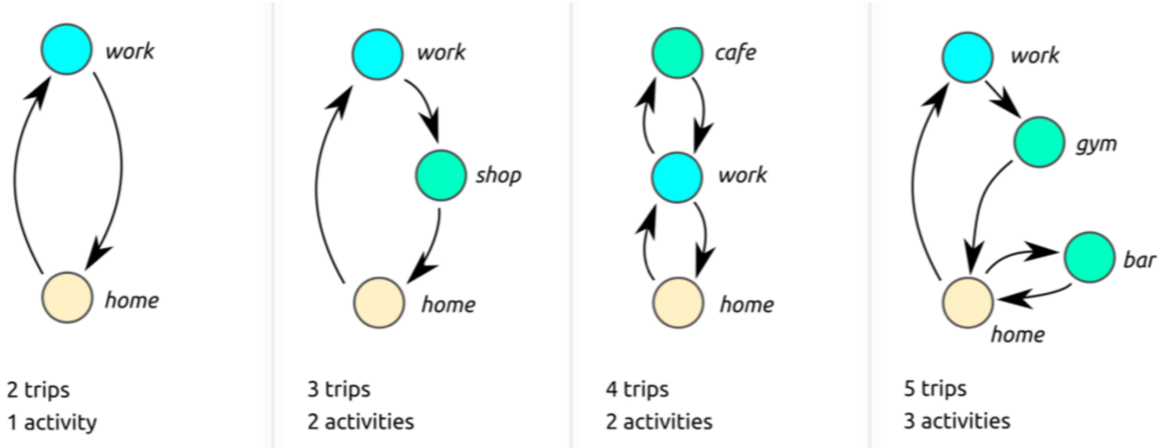


Figure 4.2: Examples of how activity participation is quantified from the travel diary.

Source: Allen and Farber (2020)

Since the OD Survey does not account for individuals' race, we tried to incorporate this aspect by calculating the proportion of declared black people living in the hexagon where the individual lives. Although this data was taken from the AOP, it originally came from the 2010 IBGE Demographic Census.

The third database used was the 2010 Paulista Index of Social Vulnerability (IPVS) produced by the Legislative Assembly of the State of São Paulo. The IPVS is calculated based on information from the 2010 IBGE Demographic Census and considers information on income, health, participation in the labour market, access to public services and opportunities for social mobility. The IPVS is divided into six levels that vary according to the combination of these variables; however, for this study, we chose to consider only two categories: living in a region of high social vulnerability and not living in a region of high social vulnerability.

After merging the different databases to the OD Survey data and generating the new variables based on this data, we excluded observations that were not complete, resulting in a sample of 47167 individuals (n = 47167). The data wrangling and descriptive statistics were performed using R 4.1.0 (R Core Team, 2021).

Table 4.2 summarises and describes the final database variables.

Table 4.2: Description of the database variables

Variable	**Description**	**Source**
NATIV_TOTAIS	Number of activities in which the individual participated	Generated from the 2017 São Paulo OD Survey
NATIV_TRAB_-EST	Number of mandatory (employment or study) activities in which the individual participated	Generated from the 2017 São Paulo OD Survey
NATIV_DISC	Number of discretionary activities in which the individual participated	Generated from the 2017 São Paulo OD Survey
VEIC_Part_Percapita	Number of private vehicles (cars and motorbikes) per family members	Generated from the 2017 São Paulo OD Survey
RENDA_FA_PerCapita_1000	Family income divided by the number of people in the family (in thousands of Reais)	Generated from the 2017 São Paulo OD Survey
TP_CMATT30	Percentage of the total number of jobs in the city of São Paulo accessible by public transport within 30 minutes travel time	Access to Opportunities Project of the IPEA
TP_CMATT60	Percentage of the total number of jobs in the city of São Paulo accessible by public transport within 60 minutes travel time	Access to Opportunities Project of the IPEA
TP_CMATT90	Percentage of the total number of jobs in the city of São Paulo accessible by public transport within 90 minutes travel time	Access to Opportunities Project of the IPEA
TP_CMATT120	Percentage of the total number of jobs in the city of São Paulo accessible by public transport within 120 minutes travel time	Access to Opportunities Project of the IPEA
SEXO	Gender (0 - Male, 1 - Female)	2017 São Paulo OD Survey
ESTUDA	Study status (1 - No, 2 - Kindergarten/Pre-school, 3 - Primary/Elementary, 4 - Secondary/Middle, 5 - Higher/University, 6 - Other)	2017 São Paulo OD Survey
GRAU_INS	Level of Education (1 - Non-Literate/Incomplete Primary I, 2 - Elementary I Complete/Incomplete Secondary II, 3 - Elementary II Complete/Middle School, 4 - Secondary Complete/Higher Education Incomplete, 5 - Higher Education Complete)	2017 São Paulo OD Survey
CD_ATIVI	Employment status (1 - Has a regular job, 2 - Does odd-jobs, 3 - On sick leave, 4 – Retired/Pensioner, 5 - Unemployed, 6 - Never worked, 7 - Housewife, 8 - Student)	2017 São Paulo OD Survey
IDADE	Age	2017 São Paulo OD Survey
NO_MORAF	Number of people in the family	2017 São Paulo OD Survey

Table 4.2: Description of the database variables

Variable	Description	Source
SIT_FAM	Family status (1 - Responsible person, 2 - Spouse / Partner, 3 - Child / Stepchild, 4 - Other Relative, 5 – Other Resident, 6 - Resident Employee, 7 - Relative of Resident Employee)	2017 São Paulo OD Survey
CO_REN_I	Has individual income (1 - Has income, 2 - Has no income, 3 - Did not answer)	2017 São Paulo OD Survey
PropNegra	The proportion of black individuals in the place where the individual lives	Generated from the Access to Opportunities Project of the IPEA
IPVS_Vuln	Paulista Social Vulnerability Index (0 - Does not live in a high social vulnerability region, 1 - Lives in a high social vulnerability region)	Paulista Social Vulnerability Index
Populational Density	The populational density in place where individual lives.	Generated from the Access to Opportunities Project of the IPEA

The descriptive statistics of the number of activities performed are presented in Tables 4.3 and 4.4. On average, individuals perform 1.1 activities per day, with the average participation in mandatory activities equaling 0.78 and discretionary activities 0.18. Approximately 3% of the sample participates in more than three activities. Regarding mandatory trips (work and study), 43.3% did not participate in any of them on the day before the OD survey, and 39.64% participated in one mandatory activity. The vast majority of the sample (83.73) did not perform any discretionary trips on the day before the survey.

Table 4.3: Univariate analysis of Dependent Variables

Activity Frequency	Mean	Std.Dev	Min	Q1	Median	Q3	Max	IQR	N.Valid
Total activities	1.10	1.05	0	0	1	1	13	1	47167
Mandatory/Fixed Activities	0.78	0.86	0	0	1	1	13	1	47167
Discretionary/Flexible Activities	0.18	0.44	0	0	0	0	7	0	47167

Table 4.4: Distribution of Dependent Variables

Total activities	n	%
0	13202	27.99
1	23152	49.09
2	5861	12.43
3	3557	7.54
>3	1395	2.96

Mandatory/Fixed Activities	n	%
0	20421	43.3
1	18696	39.64
2	6554	13.90

Table 4.4: Distribution of Dependent Variables

Total activities	n	%
3	992	2.10
>3	504	1.07

Discretionary/Flexible Activities	n	%
0	39495	83.73
1	6914	14.66
2	652	1.38
3	74	0.16
>3	32	0.07

The descriptive statistics of accessibility and independent variables are presented in Table 4.5 and 4.6, respectively. The individual with the best accessibility level accesses only 15% of the jobs in the city travelling 30 minutes by public transport. On the other hand, more than 50% of individuals access 90% of the jobs in the city of São Paulo in less than 120 minutes of travelling by public transport. The accessibility variables with intermediate threshold time, that is, 60 and 90 minutes travelling by public transport, present an average of 20% and 53% jobs accessible, respectively. The accessibility measure with a 90-minute threshold has a more homogeneous distribution of individuals in the different ranges (Table 4.7 and Figure 4.3). The spatial distribution of the four accessibility variables is depicted in Figure 4.4.

Table 4.5: Univariate analysis of Accessibility Variables

Accessibility	$\overline{x}$	s	Min	Q1	Median	Q3	Max	IQR	n
30 min	0.02	0.02	0	0	0.01	0.02	0.15	0.02	47167
60 min	0.2	0.15	0	0.06	0.17	0.32	0.66	0.26	47167
90 min	0.53	0.24	0	0.35	0.58	0.73	0.93	0.38	47167
120 min	0.83	0.17	0	0.75	0.9	0.96	0.99	0.21	47167

Table 4.6: Univariate Analysis of Independent Variables

Variable	$\overline{x}$	s	Min	Q1	Median	Q3	Max	IQR	n
Density (1000 people/km²)	15.89	11.06	0.04	8.08	13.83	21.31	71.59	13.23	47167
Age	44.93	19.2	13	29	43	60	99	31	47167
Number of people in the family	3.11	1.39	1	2	3	4	14	2	47167
Black People %	0.26	0.18	0.02	0.1	0.22	0.41	0.82	0.31	47167
Family per capita Income (R$)	2202	2293	0	847	1480	2756	52000	1909	47167
Private vehicle per capita	0.34	0.36	0	0	0.33	0.5	7	0.5	47167

Table 4.7: Accessibility levels by ranges

Accessibility Range	(30 min) n	(30 min) %	(60 min) n	(60 min) %	(90 min) n	(90 min) %	(120 min) n	(120 min) %
0%	83	0.18	18	0.04	0	0	0	0
0-10%	46720	99.05	17654	37.43	2747	5.82	96	0.2
10-20%	364	0.77	7993	16.95	3097	6.57	285	0.6
20-30%	0	0	7670	16.26	3791	8.04	500	1.06
30-40%	0	0	7561	16.03	4192	8.89	736	1.56
40-50%	0	0	5228	11.08	4887	10.36	990	2.1
50-60%	0	0	1007	2.13	6524	13.83	1926	4.08
60-70%	0	0	36	0.08	7027	14.9	4132	8.76
70-80%	0	0	0	0	9457	20.05	6015	12.75
80-90%	0	0	0	0	5307	11.25	9310	19.74
90-100%	0	0	0	0	138	0.29	23177	49.14

Table 4.8 characterises the sample according to sociodemographic variables, while Table 4.9 characterises the sample according to individuals' household location. Figures 4.5 , 4.6, and 4.7 depict the spatial distribution of income, social vulnerability, and self-declared black people in the city of São Paulo, respectively. These figures make it possible to note the city's racial, economic, and social segregation. While most people living in the centre are wealthier, white and less socially vulnerable, on the city's outskirts are the poorer, black and more vulnerable. According to the TRSE literature, the transport disadvantage is not equally or randomly distributed across society but follows the well-established lines of structural social inequality (Bocarejo S. and Oviedo H., 2012; Jaramillo *et al.*, 2012; Lucas, 2011; Ureta, 2008; Xiao *et al.*, 2018). Locations with the worst levels of transport disadvantage are also those with the worst socioeconomic conditions (Jaramillo *et al.*, 2012; Xiao *et al.*, 2018).

Table 4.8: Characterisation of the sample sociodemographics

Income Bracket (minimum wage)	n	%
0	385	0.82
<0.5	4887	10.36
0.5 - 1	12175	25.81
1 - 2	13974	29.63
2 - 3	6744	14.30
3 - 4	3551	7.53
4 - 5	1958	4.15
5 - 6	1282	2.72
6 - 7	774	1.64
7 - 8	462	0.98
8 - 9	240	0.51
9 - 10	257	0.54
>10	478	1.01

Gender	n	%
0 - Male	21625	45.85
1 - Female	25542	54.15

Employment Status	n	%
1 - Has a regular job	24175	51.25
2 - Does odd-jobs	2415	5.12
3 - On sick leave	291	0.62
4 – Retired/Pensioner	8320	17.64
5 - Unemployed	4579	9.71
6 - Never worked	166	0.35
7 - Housewife	3090	6.55
8 - Student	4131	8.76

Age Group	n	%
13 - 18	2950	6.25
18 - 29	9082	19.25
30 - 64	26714	56.64
65 - 75	4915	10.42
+75	3506	7.43

Educational Level	n	%
1 - Non-Literate/Incomplete Primary I	3071	6.51
2 - Elementary I Complete / Incomplete Secondary II	4986	10.57
3 - Elementary II Complete / Middle School	6365	13.49
4 - Secondary Complete / Higher Education Incomplete	16463	34.90
5 - Higher Education Complete	16282	34.52

Family status	n	%
1 - Responsible person	20623	43.72
2 - Spouse / Partner	11030	23.38
3 - Child / Stepchild	10712	22.71
4 - Other Relative	4045	8.58
5 – Other Resident	510	1.08
6 - Resident Employee	242	0.51
7 - Relative of Resident Employee	5	0.01

Individual Income	n	%
Yes	16889	35.81
No	9981	21.16
Did not answer	20297	43.03

Study Status	n	%
1 - No	40427	85.71
3 - Primary/Elementary	1232	2.61
4 - Secondary/Middle	1925	4.08
5 - Higher/University	3038	6.44
6 - Other	545	1.16

Number of people in the family	n	%
1	4299	9.11
2	13096	27.77
3	13119	27.81
4	10049	21.31
5	4338	9.20
6	1393	2.95
7	873	1.85

Private vehicle per capita	n	%
0	16315	34.59
<0.25	2497	5.29
0.25 – 0.50	11135	23.61
0.50 – 0.75	11450	24.28
0.75 – 1.0	737	1.56
1.0 – 1.25	4378	9.28
1.25 – 1.50	122	0.26
1.50 – 1.75	256	0.54
1.75 – 2.0	8	0.02
2.0 – 3.0	238	0.50
>3	31	0.07

Table 4.9: Characterisation of the sample according to individuals' household location

Paulista Social Vulnerability Index	n	%
0 - Does not live in a high social vulnerability region	42777	90.69
1 - Lives in a high social vulnerability region	4390	9.31

Proportion of Black People	n	%
0-10%	12205	25.88
10-20%	10170	21.56
20-30%	6120	12.98
30-40%	6261	13.27
40-50%	5734	12.16
50-60%	5452	11.56
60-70%	1174	2.49
70-80%	45	0.095
80-90%	6	0.013
90-100%	0	0

Density (1000 people/km²)	n	%

0-5	6466	13.71
5-10	9418	19.97
10-15	10267	21.77
15-20	7670	16.26
20-25	5416	11.48
25-30	3364	7.13
>30	4566	9.68

Summarising the sample activity participation and the accessibility variables in the format of boxplots (Figures 4.8, 4.9, and 4.10), we observe a clear pattern of association between higher numbers of activities performed and higher levels of accessibility. This pattern is better perceived for accessibility indicators with 60 and 90 minutes travel times.

4.4 Methodology

4.4.1 Econometric Model

The proposed econometric models intend to estimate whether accessibility influences the total, mandatory and discretionary activities carried out by individuals. More specifically, we intend to assess if higher accessibility levels cause more activity participation and, therefore, reduce the risk of TRSE. The number of activities performed is a count data: variables that assume only finite, integer and non-negative values. In many cases, count data presents several observations (counts) equal to zero (Cameron and Trivedi, 1986; Gujarati, 2008; Wooldridge, 2015).

Being the number of activities performed by the individual denoted by y and the vector of explanatory variables defined as x, we wish to estimate the $E\left(y|\ x\right)$ regression. Although the linear regression model (ordinary least squares - OLS) is widely used in most econometric studies, Wooldridge (2015) claims that a linear model may not provide the best fit for all explanatory variables in the case of a count-type dependent variable. Because the dependent variables are counts, they cannot assume negative values ($y \geq 0).E\left(y|\ x\right)$ must be non-negative for all x. Since $\hat{\beta}$ is the OLS estimator, x will eventually assume values such that $x\hat{\beta} < 0$, causing the value of y to become negative (Wooldridge, 2015).

For strictly positive values, the natural log transformation, $log\left(y\right)$, is often used in

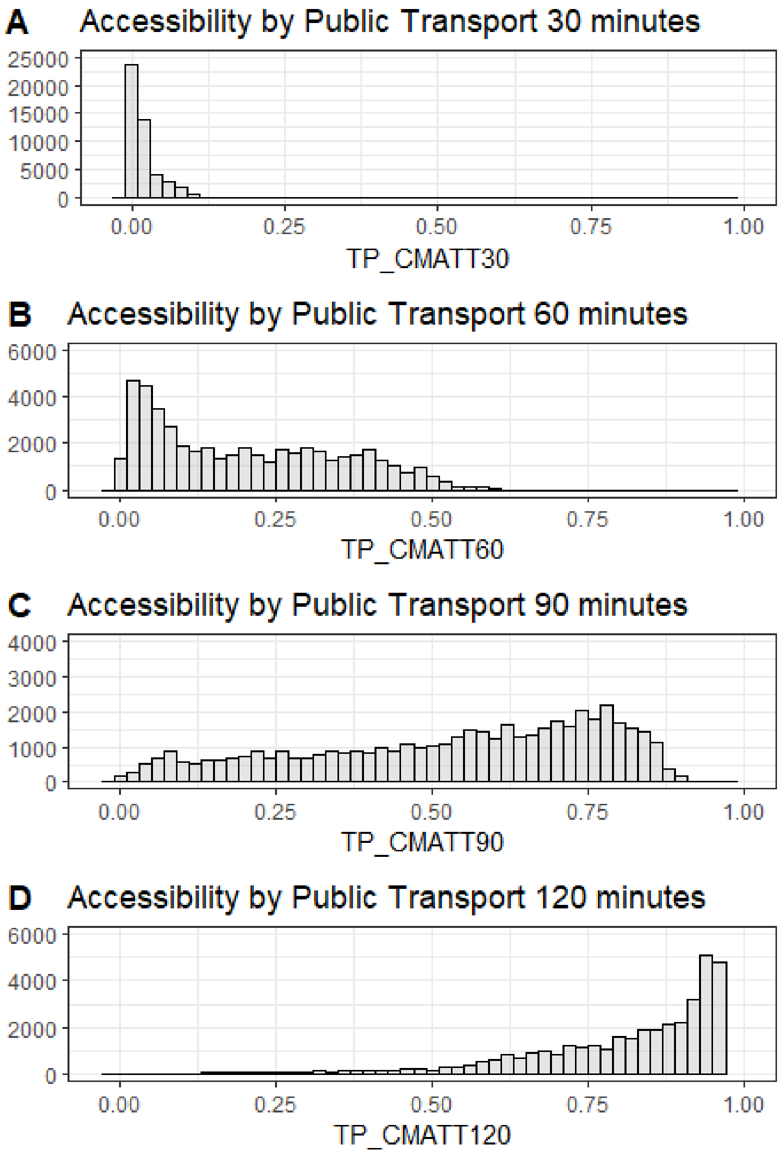


Figure 4.3: Histogram of Accessibility measures

Source: Author's elaboration

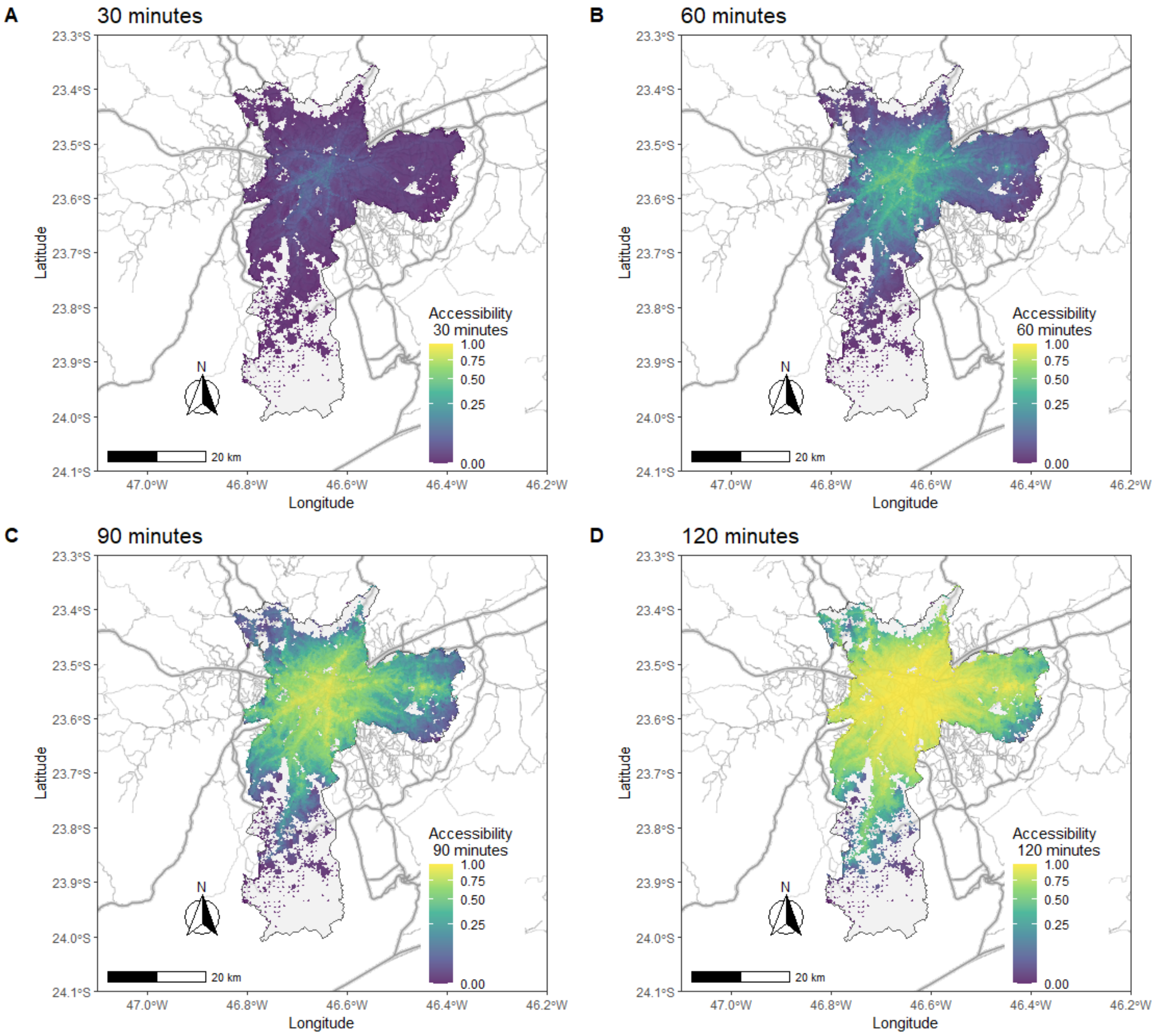


Figure 4.4: Spatial distribution of accessibility

Source: Author's elaboration

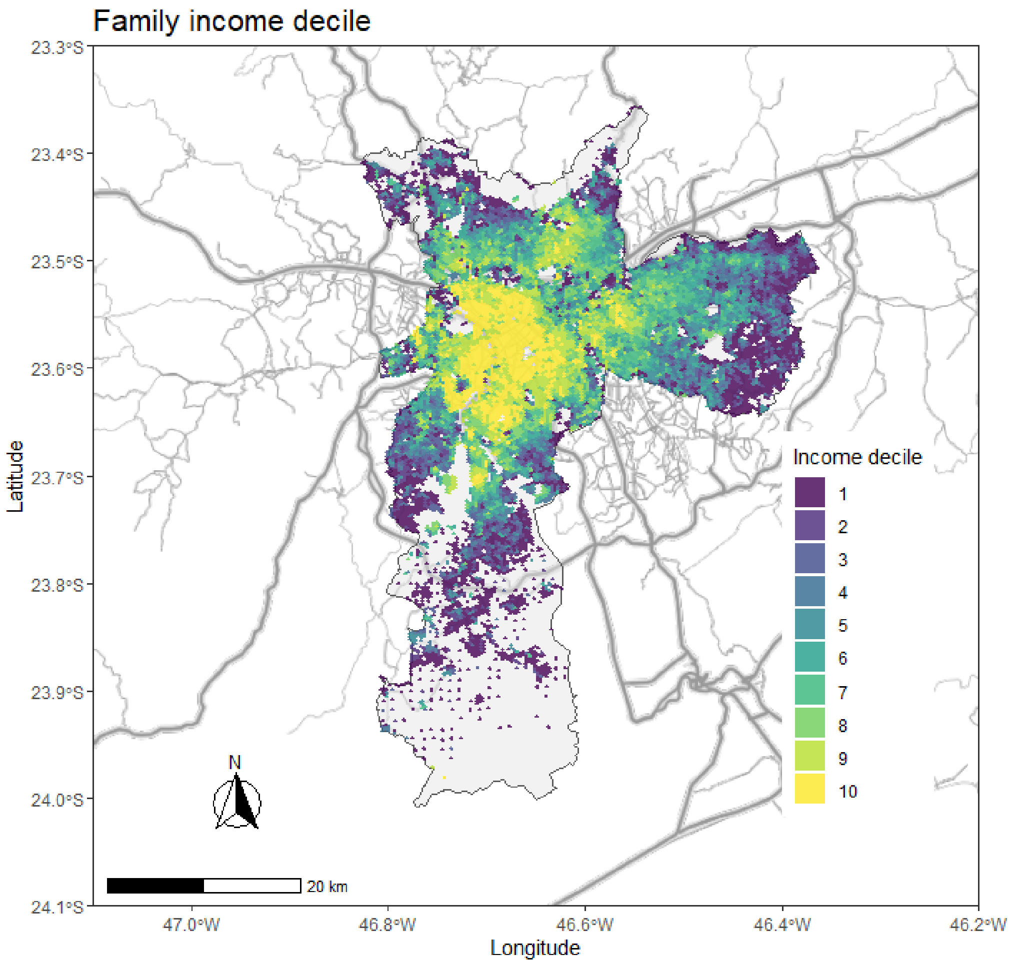


Figure 4.5: Spatial distribution of family income

Source: Author's elaboration

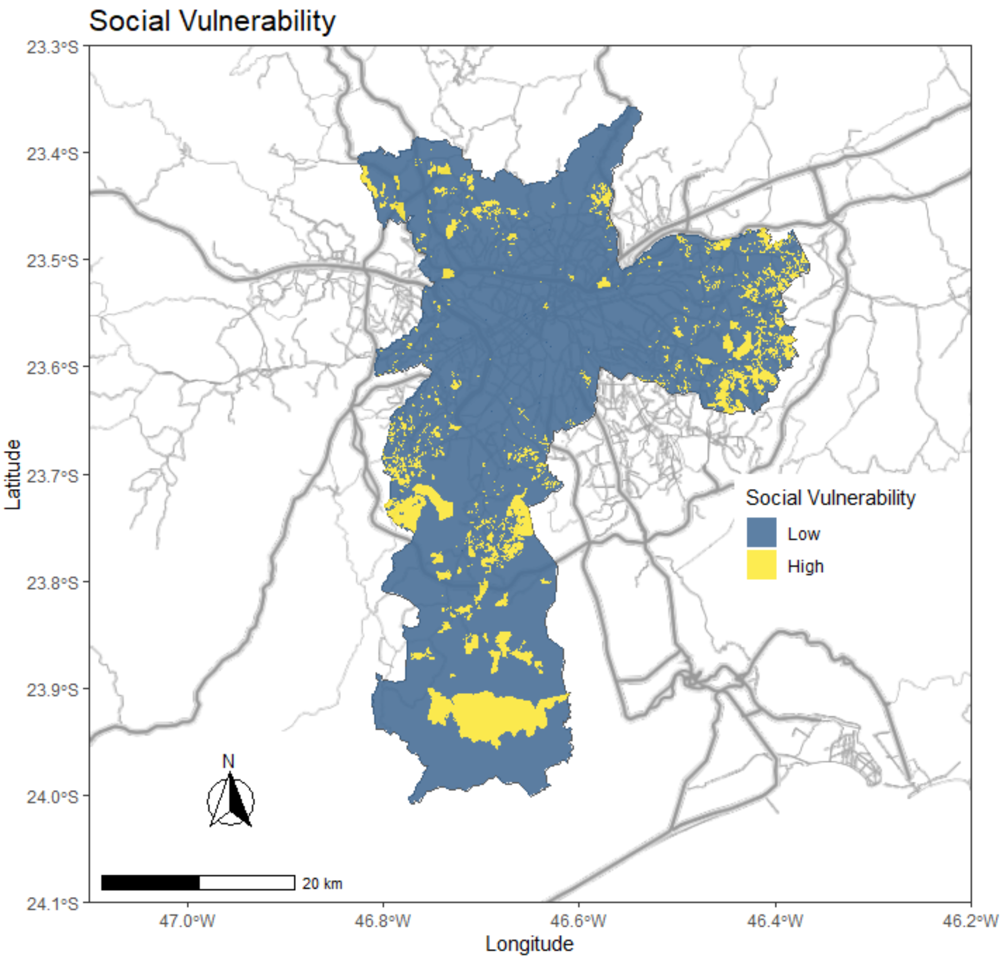


Figure 4.6: Spatial distribution of social vulnerability

Source: Author's elaboration

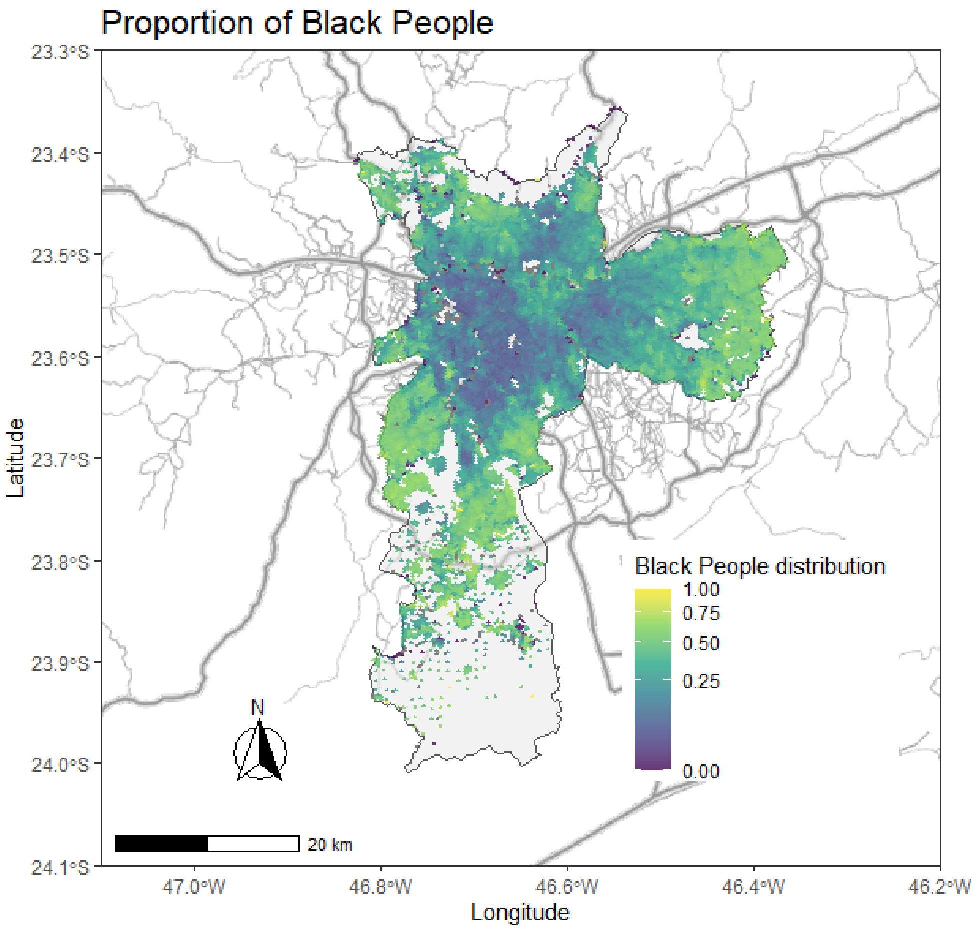


Figure 4.7: Spatial distribution of self-declared black people in the city of São Paulo

Source: Author's elaboration

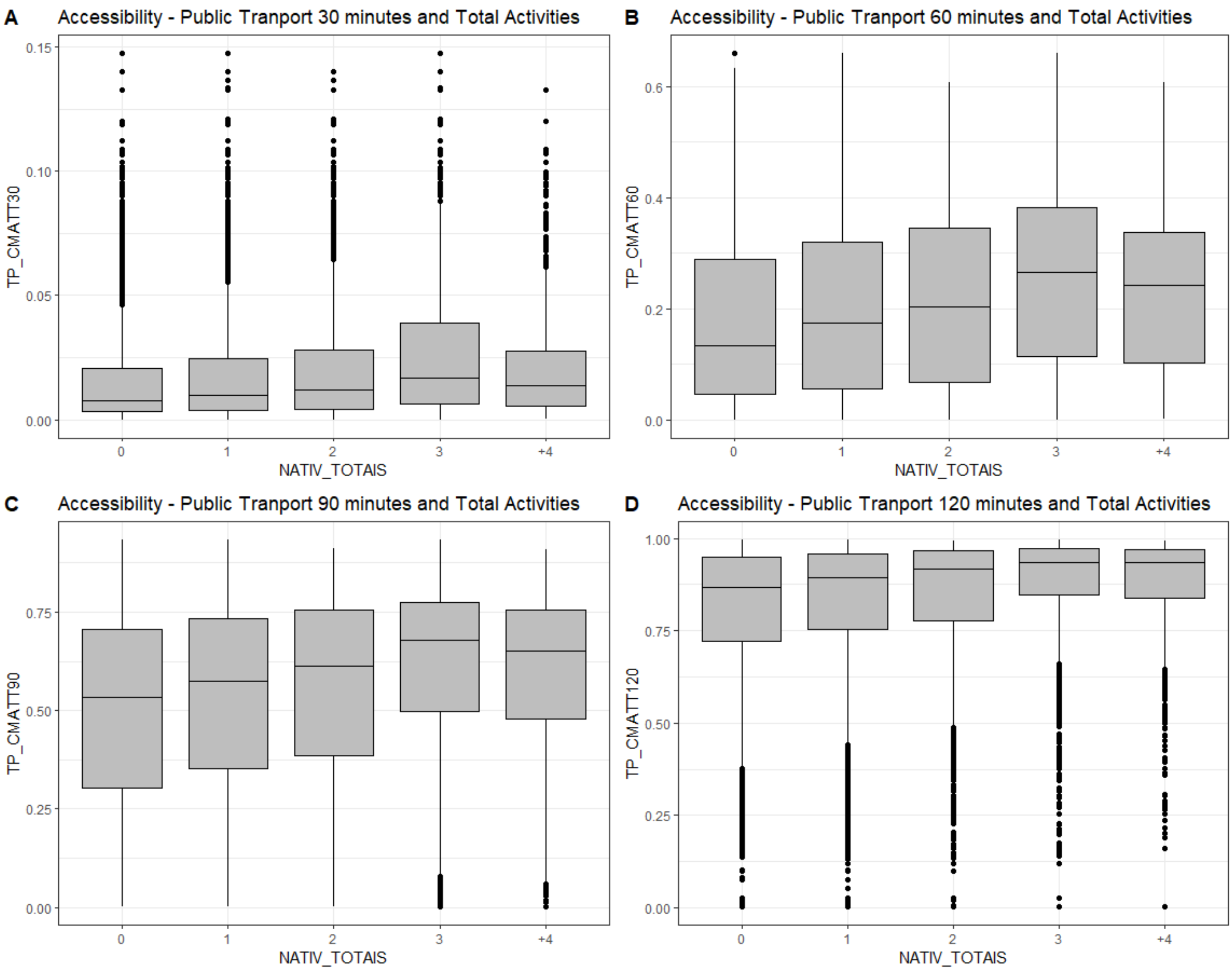


Figure 4.8: Accessibility x Total activities

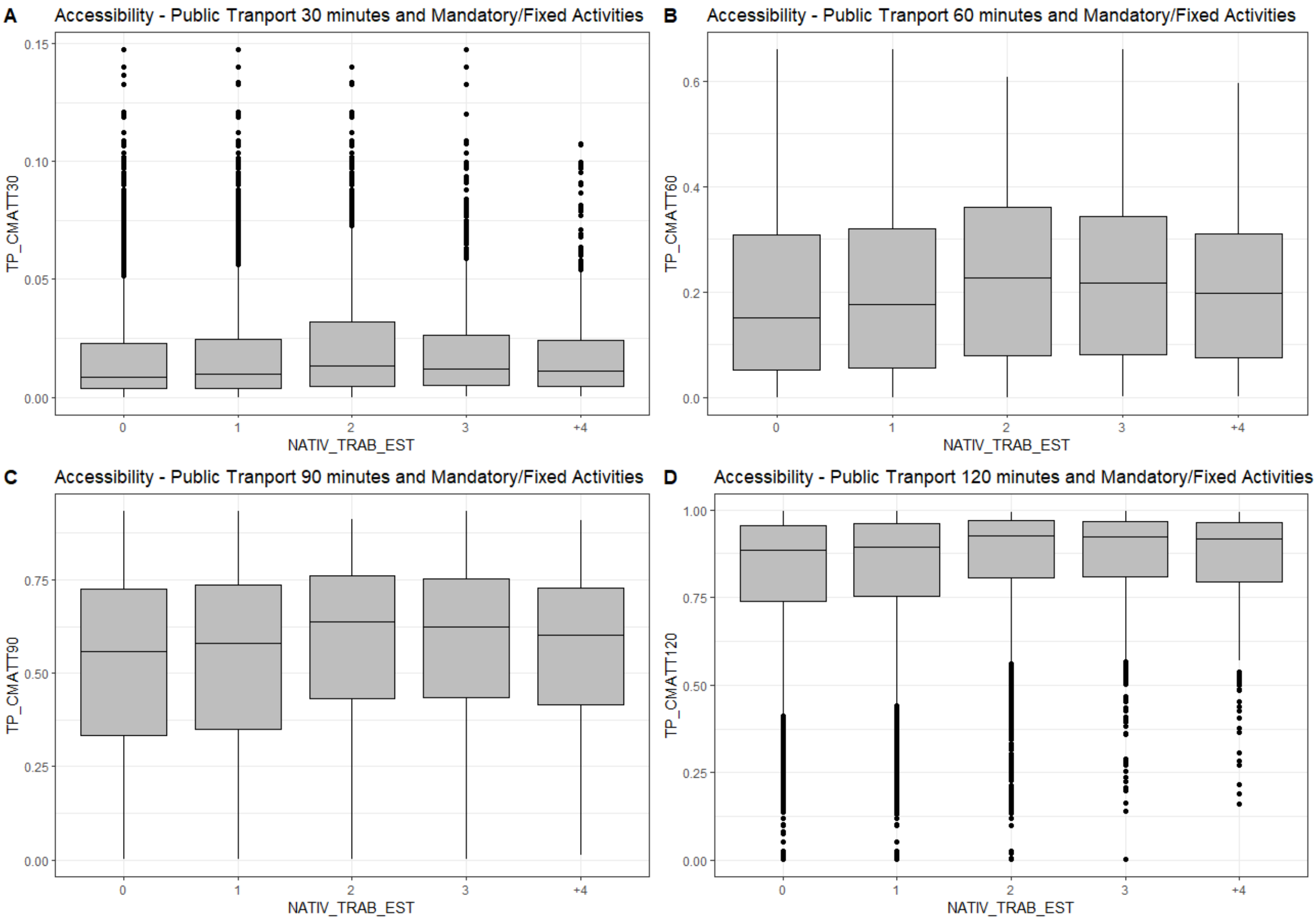


Figure 4.9: Accessibility x Mandatory/Fixed activities

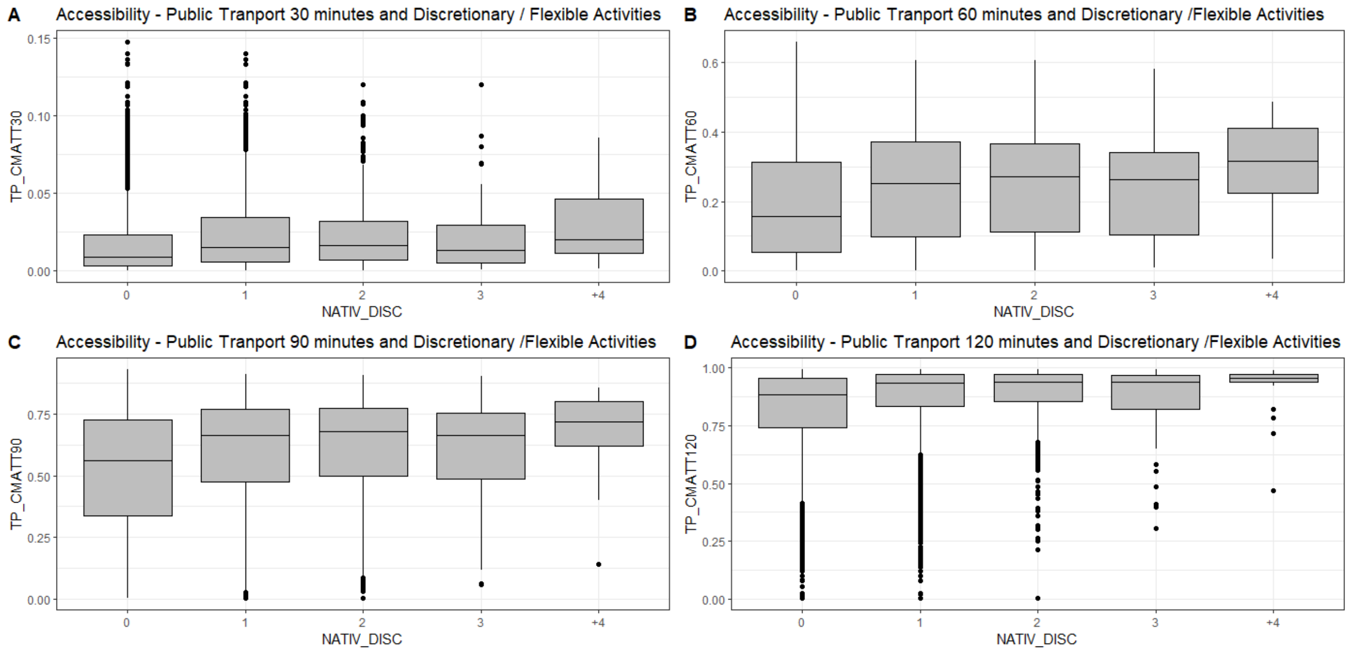


Figure 4.10: Accessibility x Discretionary activities

linear regression. However, this approach is not recommended for applications in which the proportion of the count data that assume a zero value is a non-negligible portion of the population. It will be a problem since the $log\,(0)$ is undefined (Wooldridge, 2015). Transformations can be applied to transform all y values into positive values (e.g., $log\,(y+1)$) however, Wooldridge (2015) claims that recovering $E\,[log\,(y+1)|\,x]$ is not trivial. In this sense, Wooldridge (2015) recommend modelling $E\,(y|\,x)$ directly and choosing a functional form that always guarantees positive values of y for any value of x and any parameter value.

We need a model that considers the count data's discrete nature and has a probability mass function associated only with non-negative and integer values (Cameron and Trivedi, 2005). In many count data regression analyses, the sample is concentrated on a few small discrete values (e.g., $0, 1, 2, 3$) with a high proportion of zeros. Often these data presents right-skewed asymmetry and are intrinsically heteroscedastic, with variance increasing with the mean (Cameron and Trivedi, 2005). Figure 4.11 and Table 4.10 show the right-skewed distribution of the dependent variables, the small discrete values, and the proportion of zeros in the sample. The non-normality, heteroscedasticity [1] and the

[1]Heteroscedasticity is the statistical phenomenon that occurs when the mathematical hypothesis model presents variances for $Y\ X(X_1,\ X_2,\ X_3, \ldots,\ X_n)$ that are not equal for all observations, contradicting the

discrete nature of the data violate the fundamental assumptions of linear regression

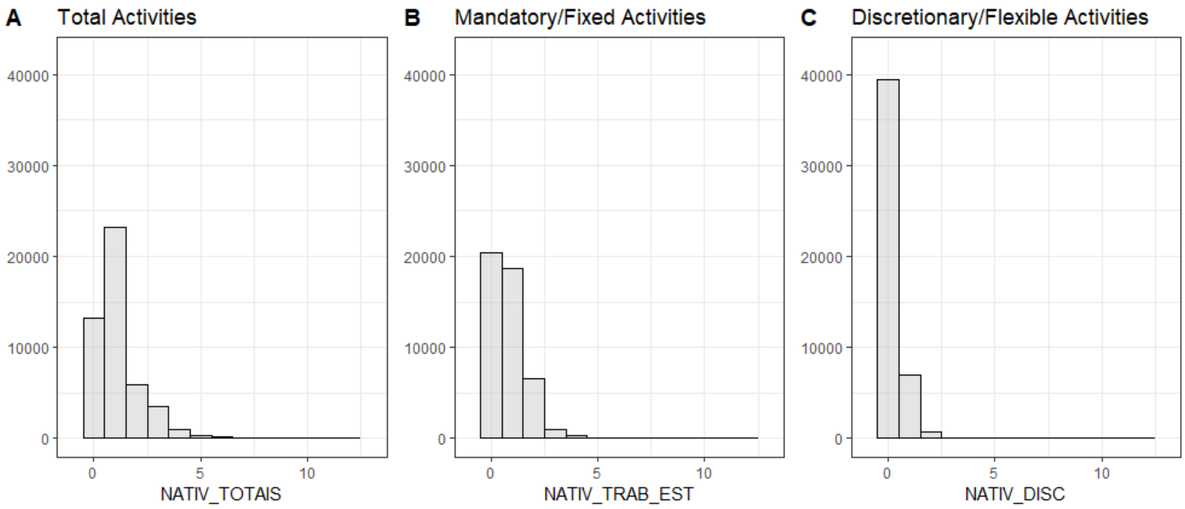


Figure 4.11: Dependent variable distribution

Table 4.10: Descriptive statistics of dependent variables

Dependent Variable	$\overline{x}$	s	s²	Min	Max	Skewness	n	% zeros
Total Activities	1.10	1.10	1.00	0	13	1.58	47167	28%
Mandatory / Fixed activities	0.78	0.86	0.74	0	13	1.39	47167	43%
Discretionary / Flexible activities	0.18	0.44	0.19	0	7	2.88	47167	84%

We need to use a probability distribution that accounts for the particular characteristics of our dependent variable. One such probability distribution is the Poisson distribution (Cameron and Trivedi, 1986; Gujarati, 2008; Wooldridge, 2015), which presents the following probability mass function:

$$P\left(y=k|\lambda\right)=\frac{e^{-\lambda}\lambda^{k}}{k!},\quad k=0,\ 1,\ 2,\ \ldots \tag{4.2}$$

where λ represents the expected number of occurrences or incidence rate ratio of the phenomenon under study for a given exposure, and k is a non-negative integer ranging from 0 to $+\infty$. The Poisson distribution is determined entirely by the mean. In particular, the variance is equal to the mean:

linear regression postulate: $var\left(u_i\right)=\ \sigma^2\ \ i=1,\ 2,\ \ldots,n.$

$$E\left(Y\right) = Var\left(Y\right) = \ \lambda \tag{4.3}$$

Equality of the mean and variance is referred to as the equidispersion property of the Poisson (Cameron and Trivedi, 2005). When the equidispersion property is satisfied, it is possible to estimate a Poisson regression model by maximum likelihood or quasi-maximum likelihood (when the equidispersion property is not satisfied) (Cameron and Trivedi, 2005) as follows:

$$\ln\left(\hat{Y}\right) = \ln\left(\lambda_i\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \ \beta_k X_{ki} \tag{4.4}$$

Thus, the expected number of occurrences in a given exposure, for a given observation i, is defined as:

$$\lambda_i = e^{\left(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_{ki}\right)} \tag{4.5}$$

Where β_0 denote the constant, $\beta_j\left(j = 1,\ 2,\ \ldots, k\right)$ are estimated parameters of each explanatory variable, X_j are the explanatory variables (metrics or dummies) and subscript i denotes each sample observation $\left(i \ = \ 1,\ 2,\ \ldots,\ n\right)$. It is worth noting that the Poisson regression model does not contain separate error terms like u in linear regression since λ determines both the mean and variance of a Poisson random variable.

The illustrative Figure 4.12 compares a linear regression model (left) and a Poisson regression model, which uses the log of λ (right). The left part of the figure shows that for each level of X, the responses are approximately normally distributed. On the right side, the plot shows that the responses follow a Poisson distribution for each value of X. For Poisson regression, small values of λ are associated with noticeably asymmetric distributions, with many small values and only a few larger ones. As λ increases, the distribution of responses resembles a normal distribution. In the linear model, the variance of Y at each X level is the same (σ^2). For Poisson regression, the responses for each value of X present larger variances as the mean increases since the variance is equal to the mean. In linear regression, the means of the responses for each X level fall on a straight line. In the case of the Poisson model, the mean values of Y for each level of X fall on a curve, not a straight line, despite the log of the means having linear behaviour (Roback and Legler, 2021). The property that the variance of Y increases as X increases is in line with Martens (2016a)'s theory that the number of activities that individuals in higher accessibility strata participate in has greater variation due to personal preferences and other factors.

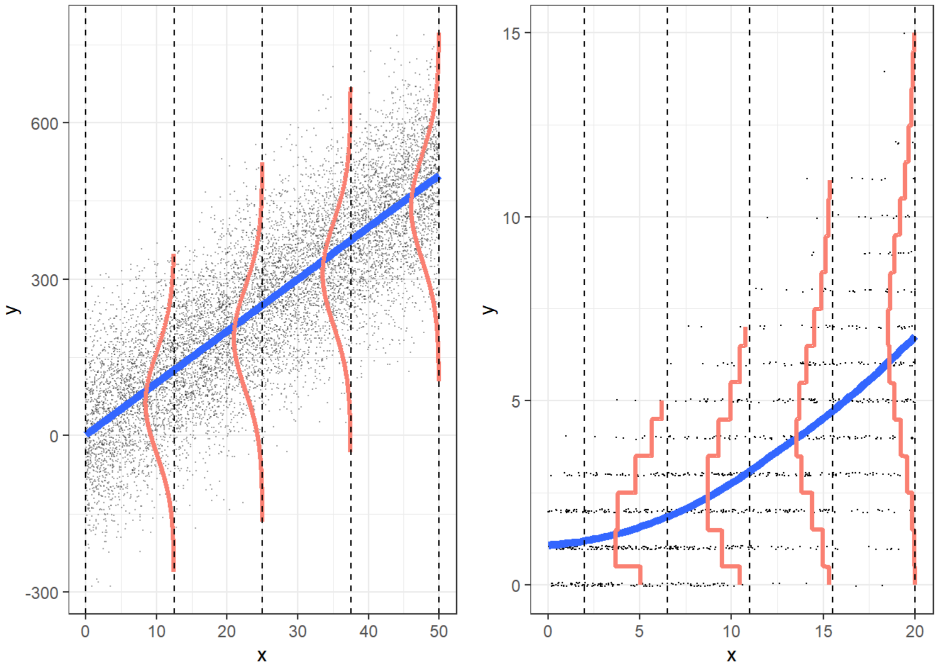


Figure 4.12: Distribution of y of linear regression (left) and Poisson regression (right)

Source: Roback and Legler (2021)

Using Poisson regression to make inferences requires the satisfaction of some model assumptions (Roback and Legler, 2021):

1. Poisson Response: The response variable is a count described by a Poisson distribution.
2. Independence: The observations must be independent of one another.
3. Mean = Variance: By definition, the mean of a Poisson random variable must be equal to its variance.
4. Linearity: The log of the mean rate, $log\left(\lambda\right)$, must be a linear function of x.

Our dependent variables are counts and follow a similar distribution to Poisson (Assumption 1). Figure 4.11 presents the histogram of the dependent variables for the entire sample. Figures 4.13, 4.14, 4.15 depict the distribution of these variables by accessibility bands.

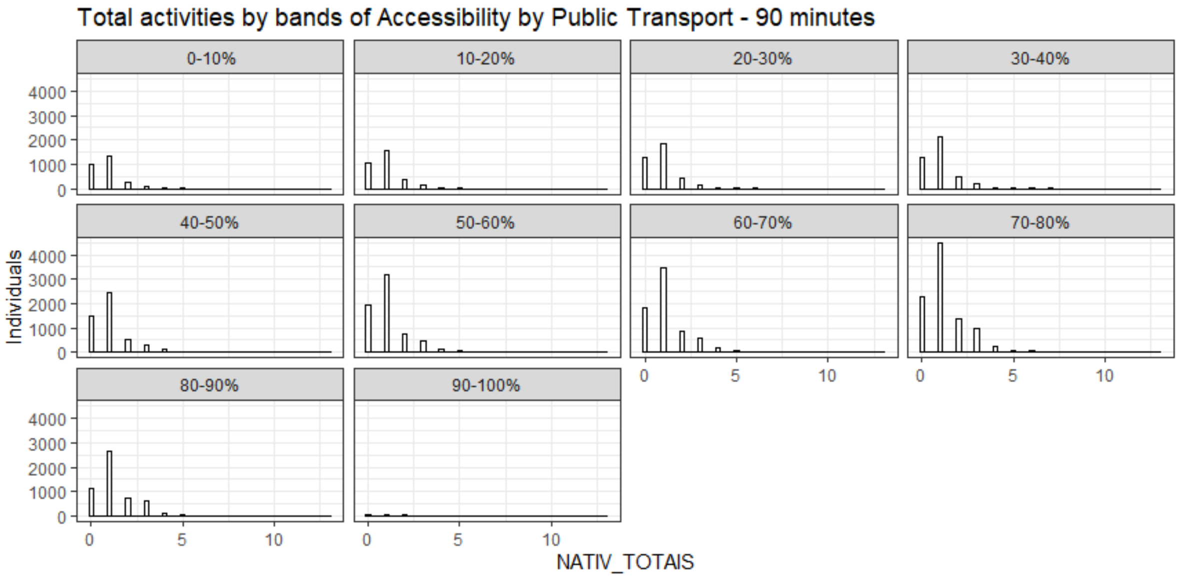


Figure 4.13: Distribution of Total activities by accessibility bands

The number of activities carried out are sourced from the 2017 São Paulo Origin-Destination Survey and are independent of each other (Assumption 2). It is possible to compare the mean and variance of the dependent variables from Table 4.10. The total activities variable has the mean exactly equal to the variance, while the variables of mandatory activities (work and study) and discretionary activities (leisure, shopping and having a meal) have variance values very close to the mean (Assumption 3). In addition, we conducted tests for overdispersion proposed by Cameron and Trivedi (1990). According to the test, the total and mandatory activities variables did not present overdispersion. On the other hand, the number of discretionary activities variable presented statistical significance for dispersion. However, the dispersion value (η) identified was tiny (0.02). Griffith (2003) suggests that if $0 \leq \eta \leq \frac{0.5}{\lambda}$, overdispersion will not pose a problem, and there will be little gain in replacing the Poisson regression model with a Negative Binomial model. For the discretionary activities model, we have $(\eta = 0.02) \leq \left(\frac{0.5}{\lambda} = \frac{0.5}{0.18} = 5.56\right)$ indicating that overdispersion will not cause problems for the Poisson regression model. Furthermore, as Cameron and Trivedi (2010) pointed out, the use of robust standard errors in the model can control for smooth violations in the equidispersion property.

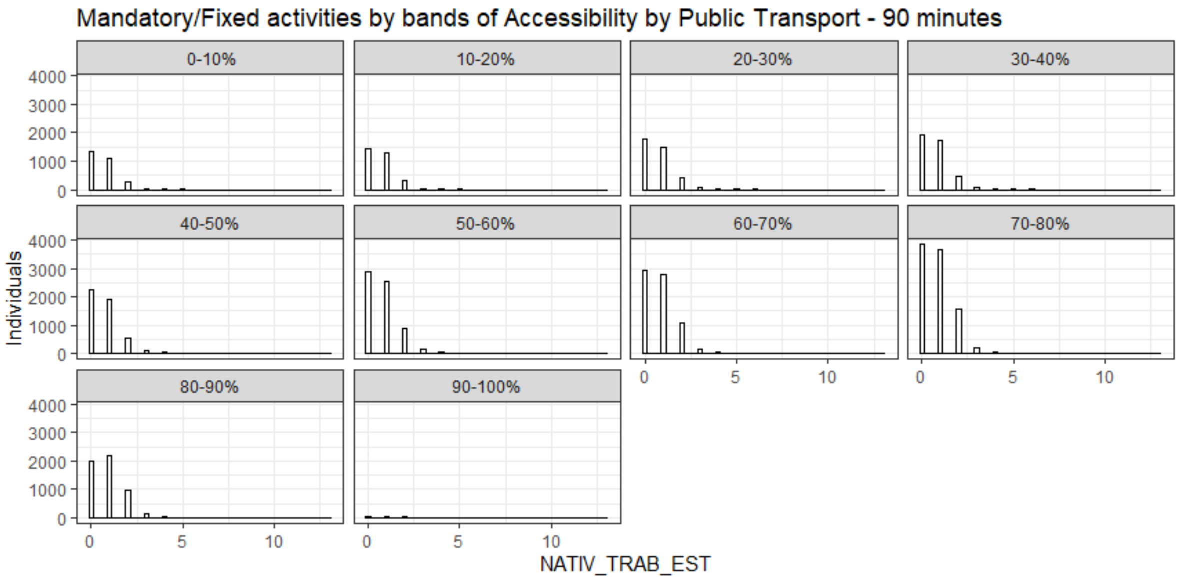


Figure 4.14: Distribution of mandatory/fixed activities by accessibility bands

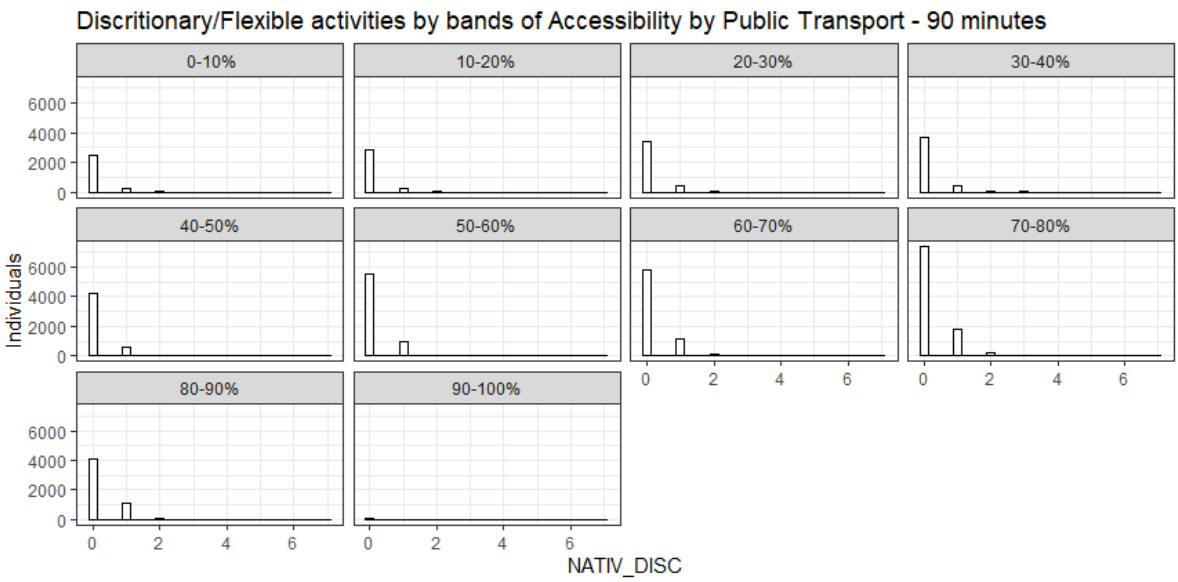


Figure 4.15: Distribution of Discretionary/Flexible activities by accessibility bands

Tables 4.11, 4.12 and, 4.13, present the mean and variance of the dependent variables by accessibility bands. The mean and variance remain very close for all dependent variables in all bands of accessibility (Assumption 3).

Table 4.11: Mean and variance of total activities variable by accessibility bands

	Total Activities			
Accessibility (90 minutes)	$\overline{x}$	s^2	$s^2/\overline{x}$	**n**
0-10%	0.88	0.79	0.90	2747
10-20%	0.91	0.78	0.86	3097
20-30%	0.93	0.85	0.92	3791
30-40%	0.98	0.90	0.92	4192
40-50%	1.02	1.02	1.00	4887
50-60%	1.07	1.10	1.02	6524
60-70%	1.17	1.21	1.04	7027
70-80%	1.25	1.29	1.03	9457
80-90%	1.28	1.17	0.91	5307
90-100%	1.35	1.45	1.08	138

Table 4.12: Mean and variance of mandatory/fixed activities variable by accessibility bands

	Mandatory / Fixed Activities			
Accessibility (90 minutes)	$\overline{x}$	s^2	$s^2/\overline{x}$	**n**
0-10%	0.67	0.62	0.92	2747
10-20%	0.69	0.62	0.90	3097
20-30%	0.71	0.68	0.97	3791
30-40%	0.72	0.66	0.91	4192
40-50%	0.73	0.71	0.98	4887
50-60%	0.78	0.75	0.96	6524
60-70%	0.83	0.79	0.95	7027
70-80%	0.85	0.83	0.97	9457
80-90%	0.88	0.74	0.84	5307
90-100%	0.94	0.77	0.82	138

Table 4.13: Mean and variance of discretionary/flexible activities variable by accessibility bands

	Discretionary / Flexible Activities			
Accessibility (90 minutes)	$\overline{x}$	s^2	$s^2/\overline{x}$	**n**
0-10%	0.10	0.11	1.14	2747
10-20%	0.10	0.11	1.09	3097
20-30%	0.11	0.11	1.00	3791
30-40%	0.13	0.14	1.12	4192
40-50%	0.16	0.18	1.12	4887
50-60%	0.17	0.17	1.00	6524
60-70%	0.21	0.22	1.09	7027
70-80%	0.25	0.26	1.07	9457
80-90%	0.25	0.26	1.03	5307
90-100%	0.25	0.31	1.21	138

The reported results are limited to accessibility by public transport calculated by the cumulative opportunities measure with a threshold of 90 minutes. The thresholds of 30, 60 and 120 minutes were also tested. However, the 90 minutes threshold accessibility variable presents a higher residual deviation after its introduction in each model (Table 4.14). It means that the accessibility variable with the 90 minutes threshold best explains the dependent variables (Roback and Legler, 2021). In addition, the 90 minutes threshold accessibility variable was the one that had the closest linear relationship with the log of the dependent variables (Figure 4.16, 4.17 and 4.18) (Assumption 4). Quadratic and cubic specifications for accessibility variables were tested to assess the best fit for the mathematical relationship between accessibility-activity participation, according to the discussion in section 4.2.2. However, the best specification for all three models was a linear relationship of accessibility variable and the log of the dependent variables.

Table 4.14: Residual deviance drop after introduction of accessibility variables in the models

	Residual Deviance Drop		
Accessibility	**Total Activities**	**Mandatory / Fixed Activities**	**Discretionary / Flexible Activities**
30 minutes	484.79	201.41	431.24
60 minutes	766.99	279.81	740.42
90 minutes	802.90	286.51	805.33
120 minutes	680.24	233.36	729.44

The explanatory variables related to the socio-demographic information of individuals and the characteristics of the region where the individual lives were also added to the models. Such variables were selected based on the transport-related social exclusion literature and previous works on the relationship accessibility-activity participation/trip making. The existence of multicollinearity was assessed using the variance inflation factor (VIF). None of the variables presented a VIF value greater than 5, indicating no multicollinearity problems among the independent variables included in the models. Moreover, LOESS type non-linear models were used to assess the relationship between independent variables and the number of activities carried out. The LOESS modelling method reveal patterns and trends in data, fitting segments of the data through a moving window-smoother, which performs a regression for each point based on the neighbouring points and their values. Some variables, such as family income per capita, age and number of residents in the household, presented a quadratic relationship with the log of the number

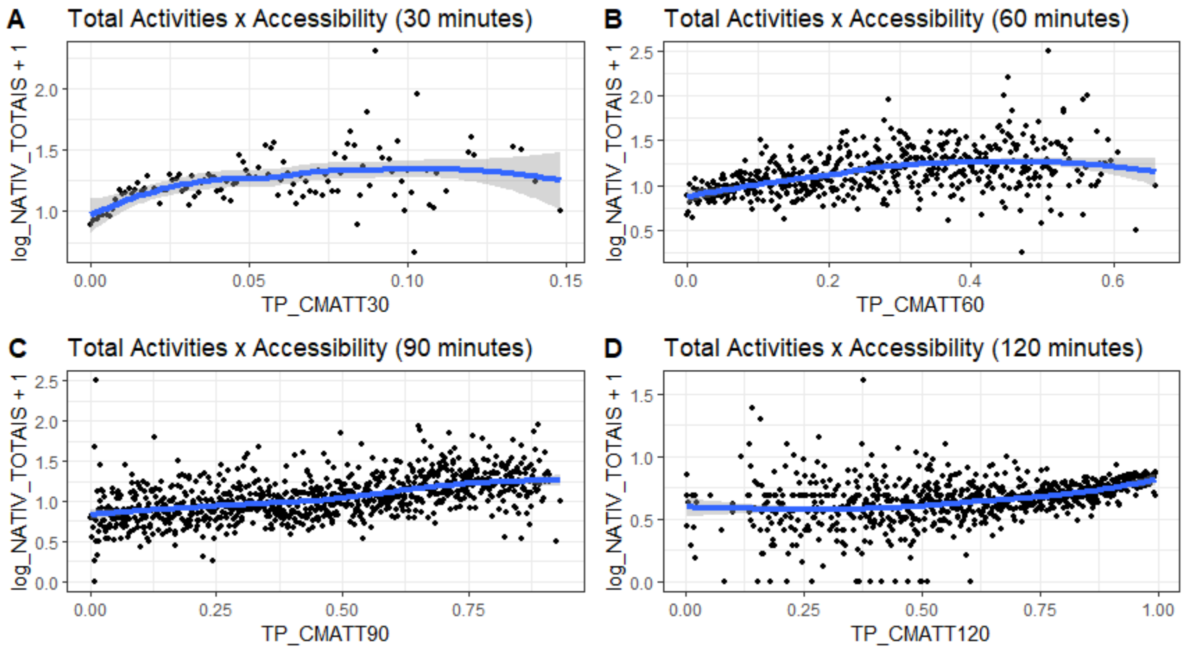


Figure 4.16: Relationship between accessibility and the log of the total activities variable

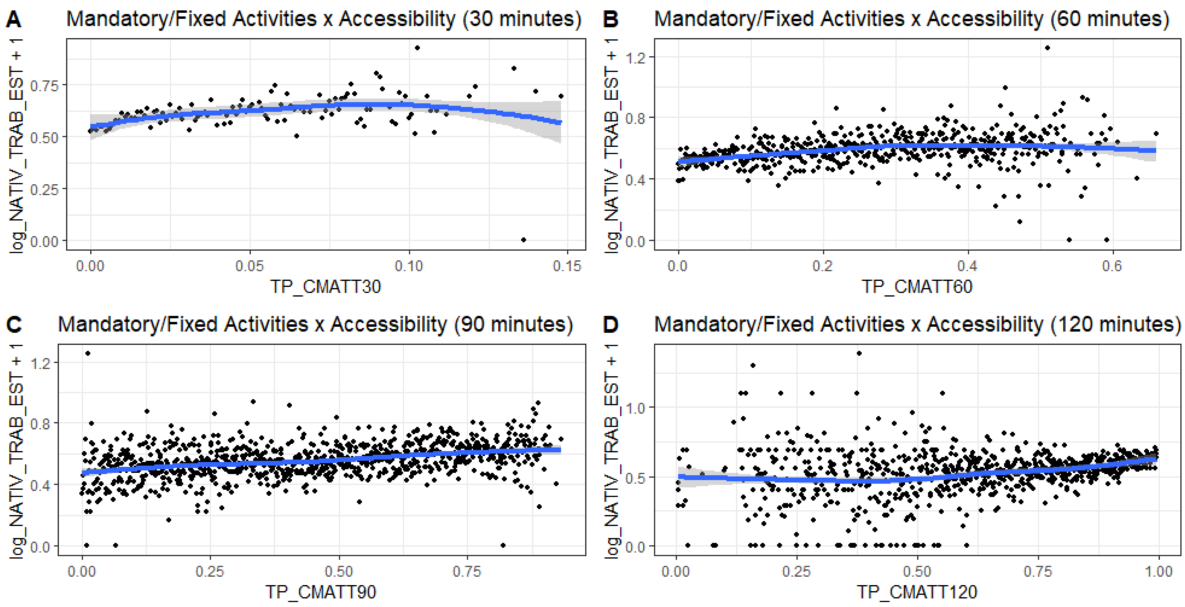


Figure 4.17: Relationship between accessibility and the log of the mandatory/fixed activities variable

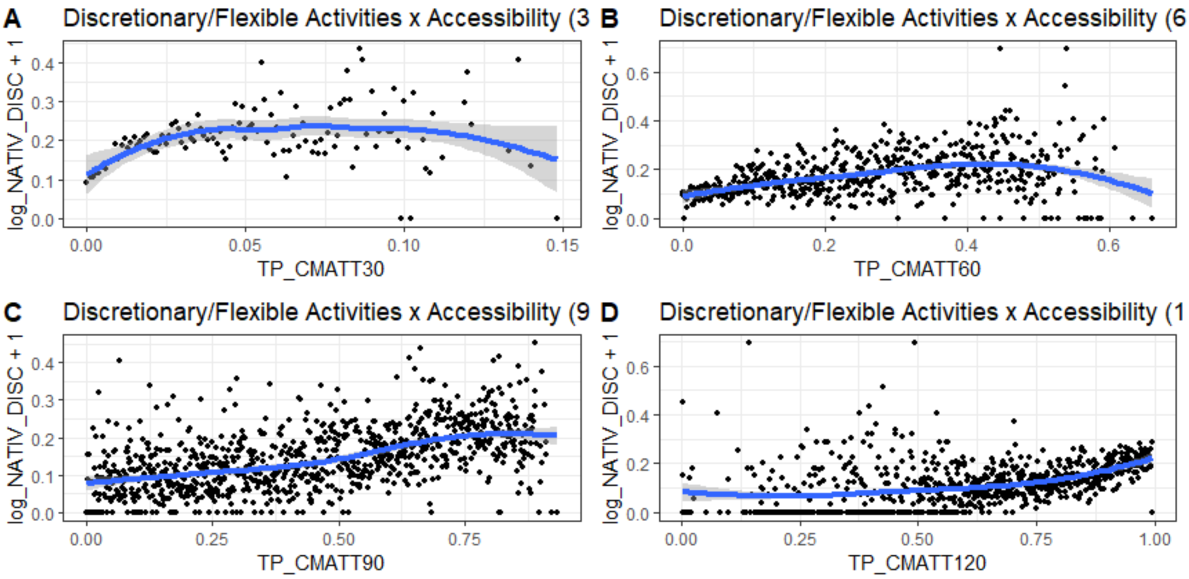


Figure 4.18: Relationship between accessibility and the log of the discretionary/flexible activities variable

of activities. Only the variables that presented a drop in the residual deviance (increased the model's explanatory power) were added to the model. The best models were selected using Akaike's information criterion (AIC) (Akaike, 1973). The AIC is a metric for estimating model prediction error, where lower values represent a better explanatory power and higher simplicity, i.e., a superior model.

Given the large proportion of zeros in the sample (4.10), many might think that perhaps a zero-inflated model would offer a better fit to the explanatory variables. Zero-inflated models are considered a mixture between a model for count data and a model for binary data (Lambert, 1992). The zero-inflated Poisson model is estimated from a Bernoulli and a Poisson distribution. This model is only recommended when the number of zeros in the sample is excessive. However, the large proportion of zeros does not necessarily mean an excess of zeros. Evaluating Poisson distributions with incidence rates (λ) equal to the mean for the dependent variables in the models (number of total activities, number of mandatory activities and number of discretionary activities), we found that the number of zeros in the sample is within the expected for such distributions (Table 4.15). In this sense, there is no necessity to use a zero-inflated model.Cameron and Trivedi (1998) point out another reason for using zero-inflated models is when observations are misrecorded, with the misrecording concentrated exclusively in the zero class. However, this is not the case for the 2017 São Paulo OD survey data.

Table 4.15: Proportion of zeros in a Poisson distribution with λ equal to the mean of the dependent variables

Dependent Variable	$\overline{x}$	**s²**	**% of zeros in a Poisson distribution with $\lambda = \overline{x}$**	**% of zeros in the sample**
Total Activities	1.1	1.1	33%	28%
Mandatory / Fixed Activities	0.78	0.74	46%	43%
Discretionary / Flexible Activities	0.18	0.19	84%	84%

Finally, the Poisson regression models for estimating the number of activities performed were defined as follows:

$$\lambda_{NATIV_{TOTAIS}} = exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3) \tag{4.6}$$

$$\lambda_{NATIV_{TRABEST}} = exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3) \tag{4.7}$$

$$\lambda_{NATIV_{DISC}} = exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3) \tag{4.8}$$

where,

$\lambda_{NATIV_{TOTAIS}}$ – Total activities in which the individual participated.

$\lambda_{NATIV_{TRABEST}}$ – Mandatory / Fixed activities (work and study) in which the individual participated.

$\lambda_{NATIV_{DISC}}$ – Discretionary / Flexible activities (leisure, shopping and having a meal) in which the individual participated.

β_0 – Intercept.

X_1 – Accessibility by public transport variable calculated from the CUM measure with a 90 minutes threshold.

X_2 – Vector of variables with individual sociodemographic information.

X_3 – Vector of variables with information regarding the urban environment of individuals residence

$\beta_1,\ \beta_2,\ \beta_3$ – Coefficients or coefficient vectors of the respective independent variables

In order to avoid endogeneity problems in the model and to infer causality between the level of accessibility and the number of activities carried out, we adopted an instrumental variable identification strategy. The following section describes the strategy and presents the reasoning for selecting the instrument. The models for the total, mandatory, and discretionary activities dependent variables before the application of the instrument are available in the Appendix B. The three models were developed using R version 4.1.0 (R Core Team, 2021).

4.4.2 Endogeneity and Instrumental Variable

In a regression, the error or disturbance term represents factors other than x that affect y. When one of the independent variables correlates with the regression error term (u), this variable is endogenous (Wooldridge, 2015). In the presence of endogenous variables, the consistency of the estimators is compromised, preventing the identification of a cause-effect relationship between the explanatory and dependent variables. Wooldridge (2015) lists three traditional sources of endogeneity in applied econometrics: measurement errors, simultaneity and omitted variables.

Measurement errors occur when we want to measure the effect of a variable (e.g. x^*), but only an imperfect measure of it is available (e.g.x). When x is added in the regression instead of x^*, we necessarily add a measurement error in u. Simultaneity, in turn, arises when one of the explanatory variables is determined simultaneously with y. If x is partially determined as a function of y, then x and u are correlated. Finally, the endogeneity problem generated by omitted variables occurs when one wishes to control the regression by one or more additional variables, but, usually due to the unavailability of data, it is not possible to include them in the model. If there is an omitted variable in the model, it is incorporated into the error term. If this omitted variable is correlated with any of the explanatory variables already in the model (which is quite common), there will necessarily be a correlation between an explanatory variable and the error term (Wooldridge, 2015).

To ensure the consistency of the estimators and thus infer causality, it is necessary to adequately control the endogeneity existing in the model in terms of the relationship between the accessibility level and the individual's participation in activities. In the case of the models under study, it is likely that there are no simultaneity problems; however, it is plausible that there is an endogeneity problem due to omitted variables and measurement errors. The number of activities performed by the individual is likely endogenous concerning several individual factors that the accessibility measure does not capture, such as income, physical condition, cognitive ability, educational level, gender, age, time availability, social status, social group, occupation, perception of the quality of public transportation, aesthetics of the urban environment, the safety of the trip, fear of crime or harassment when accessing or using public transportation, discrimination, prejudice, etc. If the regression does not include all the factors that may influence the number of activities performed by the individual, the causal effect of accessibility on the number of activities will be biased and inconsistent. Although the proposed models try to control the relationship between accessibility and individuals' participation in activities, some factors that may influence the dependent variables are not available, especially those related to an individual's perception and physical and cognitive conditions. In addition, the accessibility measure adopted only accounts for employment opportunities, disregarding other types of activities. Although accessibility to employment serves as a proxy for accessibility to activities in general (Allen and Farber, 2020; Cordera *et al.*, 2017), there is a certain degree of measurement error in this variable.

Hence, it is essential to use some identification strategy to control for endogeneity and thus infer the causal effect of accessibility on activity participation. The best way to control for endogeneity is to use natural experiments or policy-induced "quasi-random" changes in accessibility (Bastiaanssen *et al.*, 2021). Since neither of these approaches is possible due to the cross-section nature of the database, we decided to apply an identification strategy based on an instrumental variable (IV). Cunningham (2021) suggests drawing on a DAG (directed acyclic graph) 4.19 that shows a chain of causal effects to understand the IV technique.

In our model, variable Z denotes the instrumental variable, D the accessibility variable, Y the number of activities in which an individual have participated, and u are all the unobservable factors that affect both the level of accessibility and the activity participation. To control the endogeneity of D (accessibility) and be able to determine its causal effect on Y (activity participation), one must choose an instrument that meets three criteria (Cunningham, 2021):

1. Z must be highly correlated and have a causal effect on D or share a common cause;

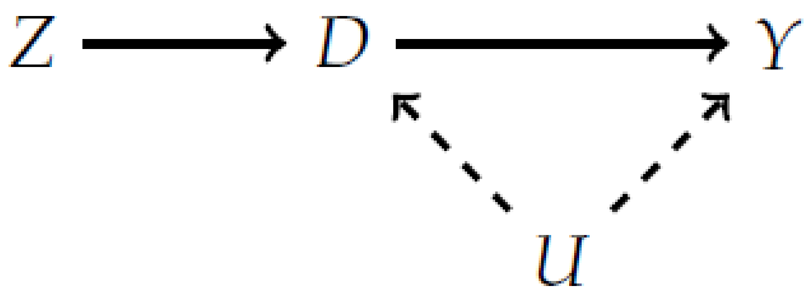


Figure 4.19: DAG (directed acyclic graph)

Source: Cunningham (2021)

2. Z must affect Y only through D. There is no direct effect of Z on Y (Exclusionary constraint).

3. Z is not correlated with or is independent of u and, therefore, does not share a common cause with outcome Y. The instrument Z must not be correlated with the regression residuals of D on Y.

The instrumental variable method allows estimating the average effect of D on Y through the instrument Z, irrespective of having measured the other (omitted) variables necessary to control for the effects (u) that may cause confusion in the estimation of Y. The instrumental variable estimator bypasses the need to adjust for confounding variables by estimating the average effect of D on Y from two effects of Z: the average effect of Z on D (first stage) and the average effect of Z on Y (second stage). These two estimated effects are consistent since Z is randomly determined and does not correlate with the errors. As a result, it is possible to identify the causal effect of D (accessibility measured by CUM) on the number of activities individuals participate in (Y).

A good instrument for our model, therefore, must be highly correlated and have a causal effect or share a common cause with the accessibility variable (endogenous variable), must affect the number of activities in which individuals participate in only through accessibility, not share common causes with the activity participation and be randomly determined. Simply put, the instrument must be correlated with the number of activities in which individuals participate only through accessibility.

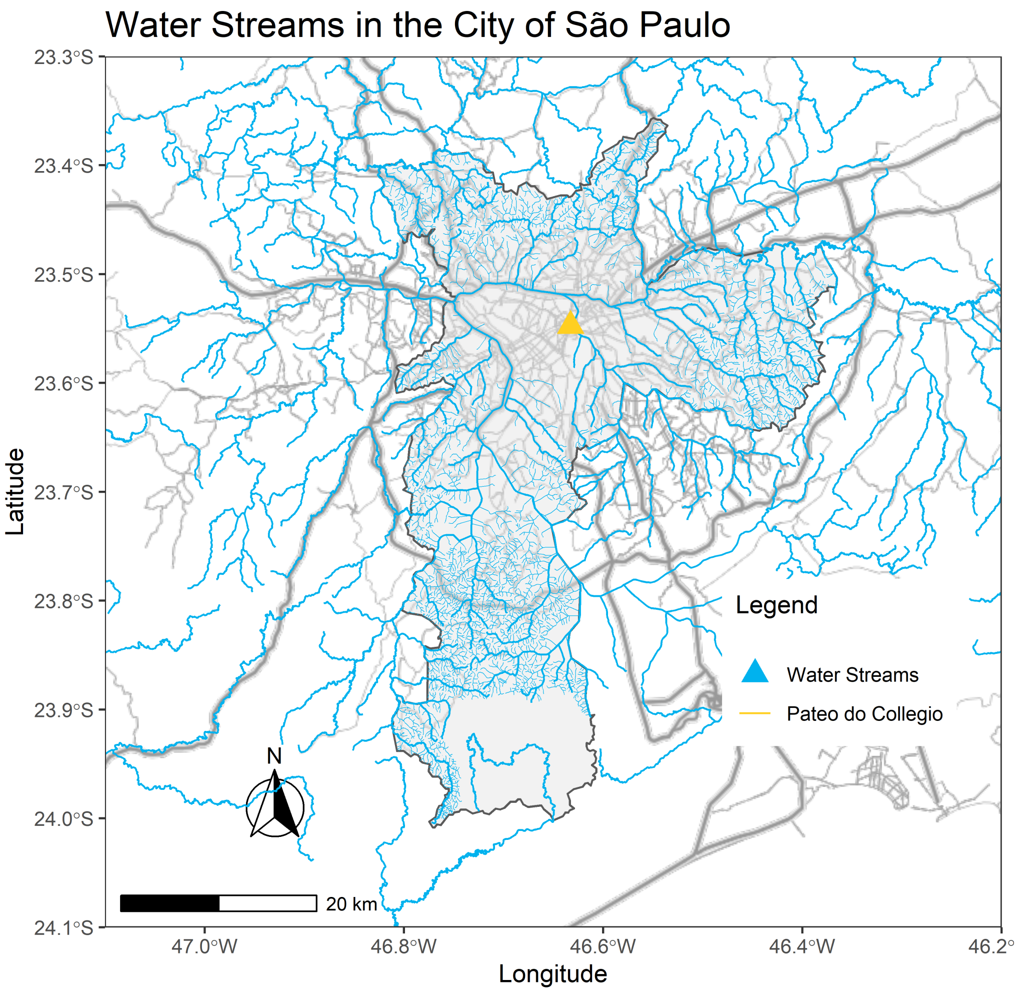
The selection of the instrumental variable was based on previous studies (Duranton and Turner, 2011; Haddad and Barufi, 2017; Jin and Paulsen, 2018), which suggest that geography is a strong determinant of transport infrastructure in a city. More specifically, the strategy adopted is the same that Haddad and Barufi (2017) used to assess the impact of accessibility on wages in the São Paulo metropolitan region. The proposed strategy is based on including a geographical/historical variable, the river shore distance to the first school built by the Jesuits in Sao Paulo, the city's founding location currently known as Pateo do Collegio. The historical maps (Figure 4.20) shows that the city has expanded around this location.

Figure 4.20: The first map of the city of São Paulo

Source: Arquivo Histórico Municipal

The instrumental variable was calculated from a georeferenced watershed database [2] where the municipality of São Paulo is located. The distance in kilometres from each location in the database to Pateo do Collegio by the nearest river shore was estimated using the Network Analysis tool of the QGIS software version 3.16.8. Figure 4.21 presents the water streams in the municipality of São Paulo, and Pateo do Collegio location.

Figure 4.21: Water Streams in the city of São Paulo



Source: Author's elaboration

Pearson's correlation coefficient between accessibility by public transport measured using the CUM measure with a 90-minute threshold and the distance to Pateo do Collegio by the nearest river shore was statistically significant and strongly correlated (-0.637). The correlation between the instrument and the three dependent variables (Total activities, Mandatory/Fixed activities and Discretionary/Flexible activities) and between the instru-

[2] Companhia Ambiental do Estado de São Paulo (2007) `https://cetesb.sp.gov.br/ughri06_hidrografia/`

ment and the estimated models' residuals presented a Pearson correlation coefficient very close to zero (0.009 for total activities, 0.004 for mandatory activities and 0.006 for discretionary activities). As a result, the instrument chosen met the third criteria previously stated.

The reasoning for the choice of the instrument was the same adopted by Haddad and Barufi (2017). According to the authors, geography acted as a determinant of the location of transport infrastructure in the region. Consequently, the road network presents a strong spatial correlation with the existing water streams before urbanisation. It means that the instrument Z, the distance to Pateo do Collegio by the river shore, was naturally/randomly determined by the region's geography, thus fulfilling one of the requirements for a good instrument.

Haddad and Barufi (2017) further provide a historical perspective on the instrument's validity. According to the authors, in the mid-nineteenth century, the city of São Paulo started a systematic occupation of the city's floodplains due to the implementation of regional and urban rail and road infrastructure. In 1929, the Plano de Avenidas prepared by Prestes Maia further reinforced the occupation of river floodplains by focusing on the development of wide avenues along the talweg. Still, according to Haddad and Barufi (2017), this conception of using the floodplains as a preferential space for circulation prevailed in the following plans of the city. Today, talweg avenues are the main arterial roads of the city of São Paulo (Meyer *et al.*, 2004). Based on geographical and historical justifications, the exogeneity of the instrument seems plausible.

Since the model estimated in the previous section is not a linear regression model, the popular technique of applying the instrumental variable via two-stage least square (2SLS) estimation is not applicable (Cameron and Trivedi, 1998). Specifically, first-stage regression of an endogenous regressor on instruments followed by second-stage Poisson regression with the endogenous regressor replaced by its first-stage predicted value leads to inconsistent parameter estimates (Windmeijer and Silva, 1997). In this case, it is recommended to use the generalised method of moments (GMM) to estimate the Poisson regression model with endogenous regressors. Considering that the Poisson regression model does not present a separate error term as in linear regression (additive error term) since λ determines both the mean and variance of a Poisson random variable, it is recommended to use multiplicative errors to estimate the model (Mullahy, 1997). Multiplicative errors treat errors (or unobserved heterogeneity) symmetrically to the regressors (Cameron and Trivedi, 1998).

After treating the endogeneity of the accessibility variable, the final models were estimated using the *ivpoisson* tool of the Stata software version 13 with the option of multiplicative and robust errors. The final models and their results are presented in the results section of this chapter.

4.4.3 Spatial Dependence

One of the problems frequently encountered in regression models with spatial nature data is to neglect spatial dependence. According to LeSage and Pace (2009), spatial dependence reflects the situation in which the values observed in a location or region depend on observations from neighbouring locations. This situation, in turn, leads to a simultaneity bias and ends up compromising the consistency of the estimated coefficients. Cordera *et al.* (2017) point out that the presence of spatial autocorrelation in the error term has been scarcely addressed by the studies about the relationship between accessibility and activity participation and trip making despite the possible bias and inefficiencies in the estimated parameters. In this sense, it is pertinent to assess whether there is spatial autocorrelation in the three proposed models to ensure the consistency of the estimators.

One way to assess spatial independence is by calculating Moran's I (Moran, 1953) for the models' residuals (Griffith, 2003). Moran's I is a spatial correlation measure to assess the correlation between a location and its neighbourhood in space. The database, composed of points, was converted into Thiessen polygons to calculate the neighbourhood/contiguity matrix and, thus, estimate Moran's I. The neighbourhood matrix most commonly used to calculate Moran's I are the queen and rook types. The queen type contiguity considers all adjacent locations sharing a border or a vertex with the analysed location as neighbours. The rook type contiguity considers as neighbours those locations that share a border with the reference location (Anselin, 1988). Moreover, neighbourhood matrices can be of different orders. A first-order neighbourhood matrix is composed only of direct neighbours of the polygon, whereas a second-order one is composed of the neighbours of the polygons‘ neighbours.

To evaluate the spatial dependence of the model, Moran's I was estimated for the three models using the two types of neighbourhood matrix (rook and queen) of first and second order. The Moran's I values found were quite low ($I \leq 0.033$), indicating that there is no need to use spatial models (Table 4.16). The inclusion of spatial variables such as accessibility, density, the proportion of the black population in the area, and social vulnerability, were probably able to predict the influence of the location on the number of activities performed.

Table 4.16: Moran's I of the three model

Model	**Neighbourhood Matrix Type**	**Neighbourhood matrix order**	**Residuals Moran's I**
Total Activities Model	Queen	First-order	0.033
		Second-order	0.013
	Rook	First-order	0.033
		Second-order	0.013
Mandatory / Fixed Activities Model	Queen	First order	0.005
		Second-order	0.001
	Rook	First-order	0.005
		Second-order	0.001
Discretionary / Flexible Activities Model	Queen	First order	0.030
		Second-order	0.006
	Rook	First-order	0.030
		Second-order	0.006

4.5 Results and Discussion

4.5.1 Sociodemographics and Activity Participation

Although we cannot infer a cause-effect relationship between the sociodemographic factors included in the model and the activity participation level, exploring the models' results for these variables can help us better understand the TRSE phenomenon (Tables 4.17, 4.18, and 4.19).

Table 4.17: Total activities model after the introduction of the IV

Total activities model after the introduction of the instrumental variable (n = 47167)					
Independent Variable	**IRR**	**Robust Std. Error**	**Z**	**P-value**	
Accessibility (90 minutes)	1.479	0.062	6.290	0.000	***
Family per capita income (in thousand reais)	1.041	0.004	9.490	0.000	***
(Family per capita income (in thousand reais))^2	0.998	0.000	-6.890	0.000	***

Age	1.016	0.002	7.360	0.000	***
(Age) ^ 2	0.999	0.000	-10.350	0.000	***
Family per capita private vehicles	1.120	0.016	6.920	0.000	***
Gender (reference "Male")					
Female	1.007	0.010	0.730	0.464	
Number of people in the family	1.081	0.012	6.020	0.000	***
(Number of people in the family) ^ 2	0.997	0.002	-1.860	0.062	.
Proportion of self-declared black population in the region	1.126	0.065	1.820	0.069	.
Study Status (reference "No")					
Primary/Elementary	2.123	0.034	21.950	0.000	***
Secondary/Middle	2.000	0.029	23.600	0.000	***
Higher/University	1.619	0.016	29.630	0.000	***
Other	1.602	0.029	16.270	0.000	***
Employment status (reference "Has a regular job")					
Does odd-jobs	0.768	0.022	-11.890	0.000	***
On sick leave	0.347	0.093	-11.320	0.000	***
Retired/Pensioner	0.528	0.021	-29.350	0.000	***
Unemployed	0.481	0.030	-23.820	0.000	***
Never worked	0.293	0.153	-7.960	0.000	***
Housewife	0.561	0.035	-16.310	0.000	***
Student	0.618	0.029	-16.500	0.000	***
Live in a high social vulnerability region (reference "No")					
Yes	0.945	0.020	-2.790	0.005	**
Level of Education (reference "Higher Education Complete")					
Non-Literate/Incomplete Primary	0.692	0.029	-12.280	0.000	***
Elementary I Complete/Incomplete Elementary II	0.770	0.024	-10.500	0.000	***
Elementary II Completo/High School Incompleto	0.799	0.021	-10.350	0.000	***
High School Complete / Higher Education Incomplete	0.870	0.013	-10.260	0.000	***
Individual income (reference "Did not answer")					
Yes	1.102	0.010	9.070	0.000	***
No	0.967	0.029	-1.140	0.254	
Populational Density	1.001	0.001	2.270	0.023	*
Family status (reference "Responsible person")					
Spouse / Partner	0.851	0.014	-11.260	0.000	***
Child / Stepchild	0.694	0.016	-22.660	0.000	***
Other Relative	0.597	0.024	-21.220	0.000	***
Other Resident	0.715	0.039	-8.460	0.000	***
Resident Employee	0.265	0.109	-12.180	0.000	***
Relative of Resident Employee	0.263	0.572	-2.330	0.020	*
Constant	0.753	0.079	-3.590	0.00	***

Note: (.) p <0.1; (*) p <0.5; (**) p <0.01; (***) p <0.001

Table 4.18: Mandatory/Fixed activities model after the IV

Mandatory/Fixed activities model after instrumental variable (n = 47167)					
Independent Variable	**IRR**	**Robust Std. Error**	**Z**	**P-value**	
Accesibility (90 minutes)	2.063	0.169	4.280	0.000	***
Family per capita income (in thousand reais)	1.021	0.009	2.330	0.020	*
Age	1.061	0.006	9.430	0.000	***
(Age) ^ 2	0.999	0.000	-11.980	0.000	***
Family per capita private vehicles	1.303	0.049	5.350	0.000	***
Gender (reference "Male")					
Female	0.965	0.033	-1.090	0.274	
Number of people in the family	1.667	0.036	14.240	0.000	***
(Number of people in the family) ^ 2	0.968	0.004	-7.630	0.000	***
Proportion of self-declared black population in the region	1.332	0.189	1.510	0.131	
Study Status (reference "No")					

Primary/Elementary	3.642	0.093	13.960	0.000	***
Secondary/Middle	3.378	0.065	18.780	0.000	***
Higher/University	2.452	0.039	22.780	0.000	***
Other	3.369	0.118	10.320	0.000	***
Employment status (reference "Has a regular job")					
Does odd-jobs	0.710	0.039	-8.870	0.000	***
On sick leave	0.071	0.223	-11.870	0.000	***
Retired/Pensioner	0.074	0.074	-34.980	0.000	***
Unemployed	0.163	0.049	-37.190	0.000	***
Never worked	0.042	0.463	-6.870	0.000	***
Housewife	0.210	0.060	-26.230	0.000	***
Student	0.407	0.037	-24.420	0.000	***
Live in a high social vulnerability region (reference "No")					
Yes	0.916	0.044	-2.010	0.044	*
Level of Education (reference "Higher Education Complete")					
Non-Literate/Incomplete Primary	0.789	0.103	-2.310	0.021	*
Elementary I Complete/Incomplete Elementary II	0.877	0.083	-1.590	0.112	
Elementary II Completo/High School Incompleto	0.865	0.060	-2.420	0.016	*
High School Complete / Higher Education Incomplete	0.913	0.041	-2.220	0.026	*
Populational Density	1.002	0.002	1.220	0.224	
Family status (reference "Responsible person")					
Spouse / Partner	0.767	0.039	-6.830	0.000	***
Child / Stepchild	0.519	0.036	-18.270	0.000	***
Other Relative	0.522	0.080	-8.130	0.000	***
Other Resident	0.519	0.055	-11.910	0.000	***
Resident Employee	0.048	0.296	-10.260	0.000	***
Relative of Resident Employee	0.196	0.556	-2.930	0.003	**
Constant	0.105	0.219	-10.310	0.000	***

Note: (.) p <0.1; (*) p <0.5; (**) p <0.01; (***) p <0.001

Table 4.19: Discretionary/Flexible activities model after the introduction of the instrumental variable

Discretionary/Flexible activities model after instrumental variable (n = 47167)					
Independent Variable	**IRR**	**Robust Std. Error**	**Z**	**P-value**	
Accesibility (90 minutes)	1.734	0.183	3.000	0.0030	**
Family per capita income (in thousand reais)	1.123	0.010	11.200	0.0000	***
(Family per capita income (in thousand reais))^2	0.9967	0.0005	-6.8500	0.0000	***
Age	1.019	0.005	3.710	0.0000	***
(Age)^2	0.999	0.000	-4.440	0.0000	***
Family per capita private vehicle	1.245	0.041	5.270	0.0000	***
Gender (reference "Male")					
Female	0.943	0.030	-1.9300	0.0530	.
Number of people in the family	0.947	0.013	-4.140	0.0000	***
Proportion of self-declared black population in the region	0.769	0.185	-1.410	0.157	
Study Status (reference "No")					
Primary/Elementary	0.810	0.184	-1.140	0.253	
Secondary/Middle	1.071	0.154	0.450	0.655	
Higher/University	0.892	0.071	-1.590	0.112	
Other	1.041	0.119	0.340	0.734	
Employment status (reference "Has a regular job")					
Does odd-jobs	1.039	0.072	0.530	0.595	
On sick leave	0.908	0.183	-0.530	0.599	
Retired/Pensioner	1.641	0.046	10.750	0.000	***
Unemployed	1.386	0.072	4.560	0.000	***
Never worked	1.022	0.308	0.070	0.944	

Housewife	1.832	0.079	7.710	0.000	***
Student	0.811	0.121	-1.730	0.083	.
Live in a high social vulnerability region (reference "No")					
Yes	0.775	0.069	-3.710	0.000	***
Level of Education (reference "Higher Education Complete")					
Non-Literate/Incomplete Primary	0.490	0.075	-9.450	0.000	***
Elementary I Complete/Incomplete Elementary II	0.590	0.062	-8.520	0.000	***
Elementary II Complete/High School Incomplete	0.597	0.059	-8.740	0.000	***
High School Complete / Higher Education Incomplete	0.672	0.033	-11.750	0.000	***
Individual income (reference "Did not answer")					
Yes	1.348	0.030	10.020	0.000	***
No	1.023	0.071	0.330	0.743	
Populational Density	1.0026	0.0013	2.010	0.044	*
Family status (reference "Responsible person")					
Spouse / Partner	0.781	0.036	-6.840	0.000	***
Child / Stepchild	0.723	0.048	-6.670	0.000	***
Other Relative	0.576	0.063	-8.700	0.000	***
Other Resident	0.997	0.116	-0.020	0.986	
Resident Employee	0.982	0.167	-0.110	0.915	
Constant	0.096	0.212	-10.990	0.000	***

Note: (.) p <0.1; (*) p <0.5; (**) p <0.01; (***) p <0.001

The per capita family income variable in all three models is statistically significant. While the income variable presented a linear relationship with the log of the mandatory activities, a quadratic relationship was observed in the total and discretionary activities models. In the mandatory activities model, the activity participation rate keeps constant when family income increases. On average, a one thousand reais increase in per capita family income is associated with a 2.06% increase in mandatory activity participation. An increase of one standard deviation in the income variable (2293 reais) is associated with 4.71% more mandatory activity participation, on average.

The quadratic relationship between the per capita family income variable and the number of total and discretionary activities shows that the increase in income among individuals with lower per capita family income has a greater impact on activity participation. This impact decreases as income increases. The income increase positively impacts total activities participation in individuals with per capita family income up to approximately 17,500 reais and on discretionary activities up to approximately 18,500 reais. Individuals with a per capita family income of 17,500 participate in 35.26% more total activities on average than those with a per capita family income equal to zero. On the other hand, individuals with a per capita family income of 18,500 reais participate in more than twice discretionary activities (114.60%) than those with no family income. After these threshold levels, the increase in income is associated with a reduction in total and discretionary participation in activities. Figure 4.22 shows how total and discretionary activities vary according to family per capita income. The dashed lines intersect the curves on the inflexion points, i.e., the point from which an increase in income has a negative impact on the number of activities carried out.

The individual income variable was included only in the total activities and discretionary activities models since simultaneity issues could emerge in the mandatory activities model. In both models in which it was included, only the Yes category presented statistical significance. People who have individual income participate, on average, in 10.20% more total activities than those who did not declare whether they have income or not, and in 34.88% more discretionary activities also compared to the reference category. These results are consistent with the TRSE literature indicating that poverty and low income represent risk factors for TRSE (Bocarejo S. and Oviedo H., 2012; Jaramillo *et al.*, 2012; Kamruzzaman and Hine, 2012; Lucas, 2011; Luz and Portugal, 2021; Ureta, 2008; Walks, 2018).

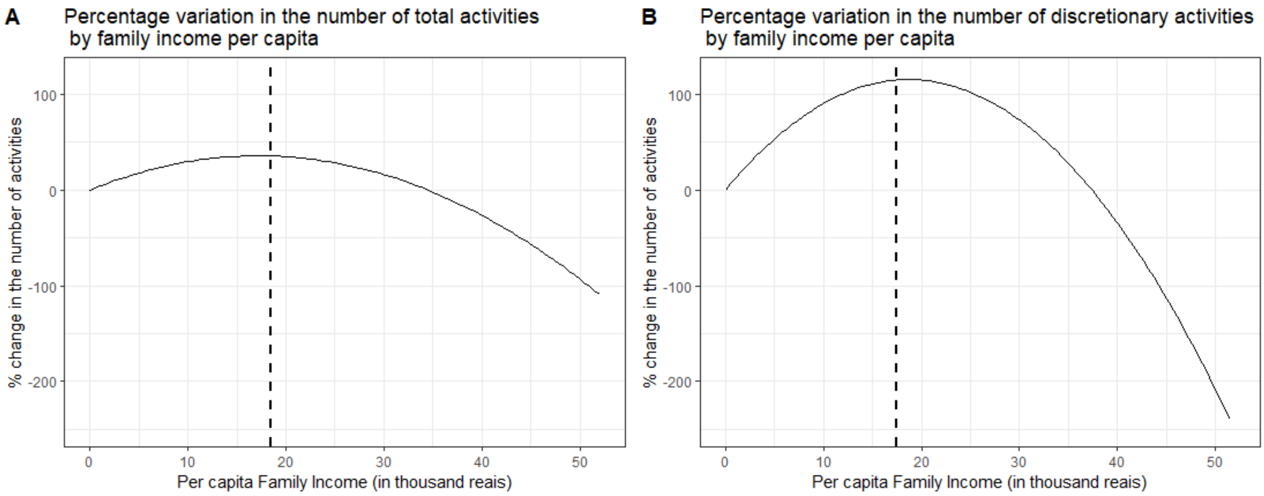


Figure 4.22: Percentage variation in the number of total and discretionary activities by family income per capita

The three models pointed out that the age variable has a quadratic association with activity participation. As age increases, the activity participation rate increase for all types of activity up to a certain threshold, where increasing age leads to a reduction in the number of activities undertaken by the individual. The age at which individuals participate in more activities is approximately 34 years for total activities, 37 years for mandatory activities and 43 years for discretionary activities (Figure 4.23). At these ages, individuals participate in 13.90% more total activities, 50.82% more compulsory activities and 24.66% more discretionary activities, on average, respectively, than their 13-year-old peers. For the elderly, the TRSE literature points out that their physical and cognitive difficulties to use public transport may put them at risk of social exclusion (Denmark, 1998; Engels and Liu, 2011; Luz and Portugal, 2021; Shergold and Parkhurst, 2012). On the other hand, younger individuals often lack the independence and safety to travel alone or are not allowed to drive and, therefore, have their ability to participate in activities limited (Denmark, 1998; Kenyon, 2003; Luz and Portugal, 2021).

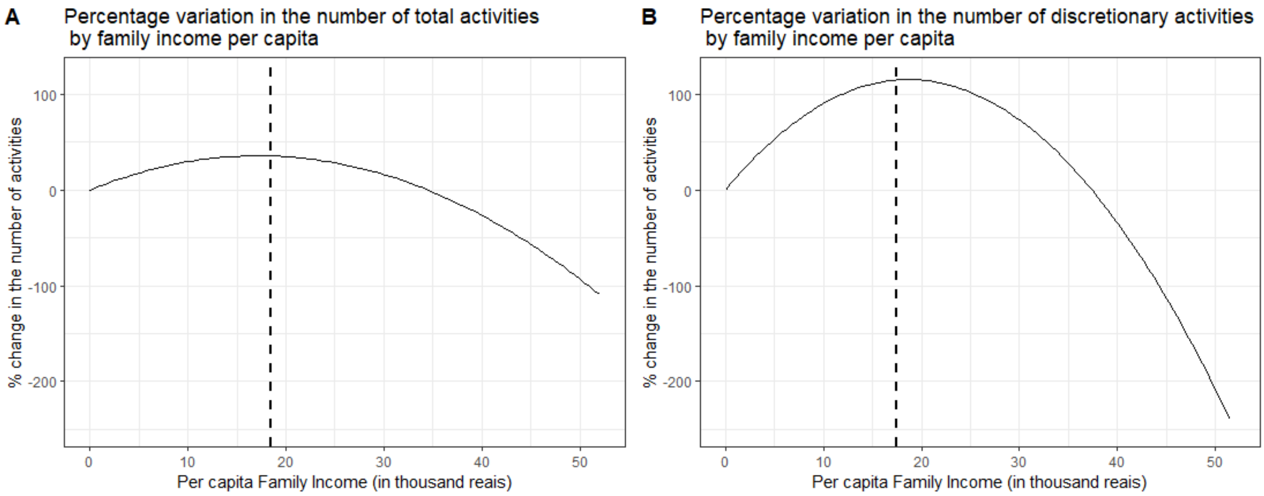


Figure 4.23: Percentage variation in the number of activities participated by age

The number of family per capita private vehicles is positively associated with activity participation. An increase of one vehicle per capita is associated with an increase of 12.03% total activities, 30.33% mandatory activities and 24.55% discretionary activities, on average. An increase of one standard deviation (0.36) is associated with increased participation in 4.33% of total activities, 10.92% mandatory activities and 8.84% discretionary activities, on average. The results are in line with the TRSE literature, which points out that households with fewer cars participate in fewer activities. The impact of carlessness is even more significant in car-dependent societies (Delbosc and Currie, 2011a; Hine, 2004; Jaramillo *et al.*, 2012; Kamruzzaman and Hine, 2012; Mattioli, 2014; Shergold and Parkhurst, 2012).

The gender variable presented statistical significance only in the discretionary activities model at the 90% level. According to the estimated model, women perform, on average, 5.66% less discretionary activities than men. Although the result not statistically significant, many studies suggest that women participate in fewer activities than men for various reasons such as: difficulties faced in participating in activities are due to personal safety/ harassment concerns when accessing public transport stations and stops (Adeel *et al.*, 2016; Casas and Delmelle, 2014; Hine and Grieco, 2003; McCray and Brais, 2007); problems of harassment in crowded public transport (Adeel *et al.*, 2016; Casas and Delmelle, 2014); and for still being the primary caregivers of their children, they face difficulties when travelling with children (McCray and Brais, 2007).

The gender variable was no longer statistically significant after introducing the family status variable in the model. The family status variable is highly statistically significant at the significance level of 99% for all three models. At first, it seems that what impacts activity participation is not necessarily the gender but the family status. However, the category Spouse / Partner, composed mainly of women, participates in fewer activities than the reference category Responsible person, composed mostly by men. Spouse/ Partner individuals participate in 14.90% fewer total activities, 23.35% fewer mandatory activities and 21.89% fewer discretionary activities on average compared to the reference category. The Child / Stepchild participates on average 30.55% fewer total activities, 48.06% fewer mandatory activities, and 27.62% fewer discretionary activities than the Responsible persons. Other relatives participate, on average, in 40.27% fewer total activities, 47.77% fewer mandatory activities and 42.31% fewer discretionary activities compared to the reference category. On average, other residents participate in 28.44% fewer total activities, 48.10% fewer compulsory activities and 0.21% fewer discretionary activities than the reference category. Further research that deepen the investigation whether the gender or the position occupied in the family impacts the level of participation in activities are necessary. We also found that retired individuals, unemployed individuals or individuals who have never worked participate in more discretionary activities than those who have a regular job. It may indicate that time availability is crucial for participation in non-discretionary activities (Fransen *et al.*, 2018a; Landau *et al.*, 1981).

The number of people in the family is associated with the activity participation level. The variation in the rate of increase in the number of discretionary activities is constant. One more individual in the family is associated with 5.24% lower participation in discretionary activities, while the variation of one standard deviation has a negative impact of 7.28%. In the total and mandatory activities models, the number o people in the family present a quadratic relationship with activity participation (Figure 4.24). The curve of the number of people in the family by the number of total activities participated reaches its maximum at 14 people. The increase rate of total activities weakens until it reaches 14 members (maximum number observed in the sample) when the curve becomes flat. On average, individuals who live with other 13 family members participate in 46.86% more total activities than those who live alone. On the other hand, the curve of the number of family members by mandatory activities reaches its maximum in 11 people. On average, individuals living with more than ten relatives participate in almost three times more (289,05%) activities than those who do not share the house with other relatives.

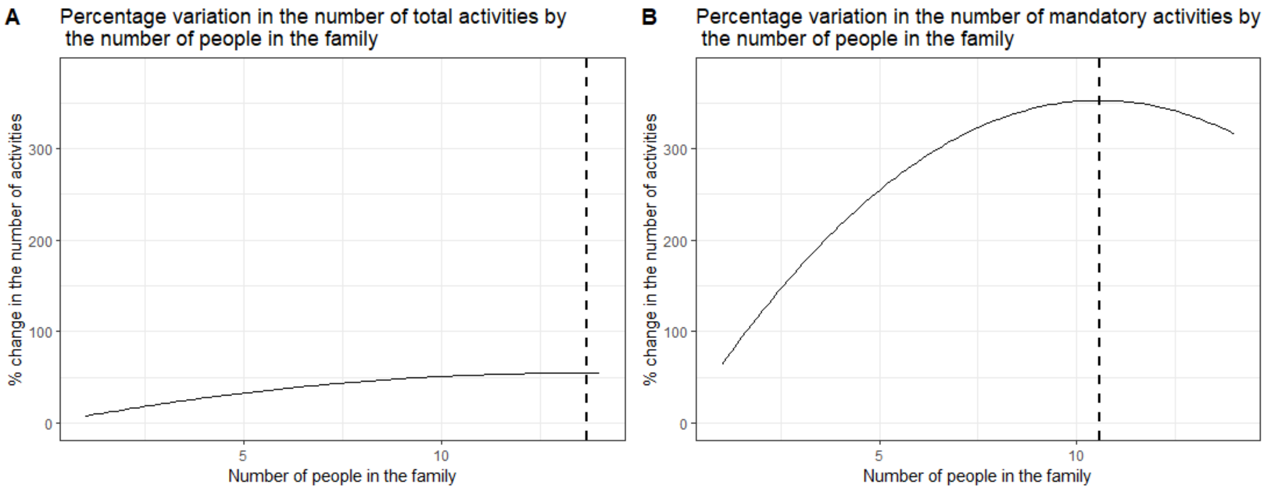


Figure 4.24: Percentage variation in the number of activities participated by the number of people in the family

The proportion of self-declared black people is only associated with the number of total activities performed. The level of statistical significance is low (90%). A one percentage point increase in the proportion of self-declared black people in the region is associated with a 0.13% higher level of participation in activities. One standard deviation (0.18) increase in the proportion of black people in the region is linked to a 2.28% increase in participation in total activities. The results may suggest that the metric adopted is inadequate to capture difficulties in activity participation due to an individual's race.

The study status variable presents statistical significance only in the total and mandatory activities models. The models indicate that people who study, on average, perform more total and compulsory activities than those who do not study. In addition, the activity participation level decreases as the schooling level increases. On average, people in the Primary/Elementary category participate in 112.33% more total activities and 264.19% more mandatory activities than people who do not study. Those in Secondary/Middle participate in 100.09% more total activities and 237% more mandatory activities on average than the reference category. Those in Higher Education, on the other hand, participate in 61.94% more total activities and 145.22% more mandatory activities, on average. On average, people who study but do not fit into the previous categories have higher participation in total and compulsory activities, 60.23% and 236.94%, respectively, than those who do not study.

The individual's employment status proved to be statistically significant in explaining the number of activities performed. While all categories of employment status had statistical significance at the 99.9% level for the total activities and mandatory activities models, only three categories showed the same results in the discretionary activities model (Retired/Pensioner, Unemployed, Housewife). In the total and mandatory activities models, all categories participate, on average, in fewer activities than individuals who work regularly. On average, people doing odd jobs participate in 23.17% fewer total activities and 29.04% fewer mandatory activities than regular workers. On average, people on sick leave participate in 65.22% fewer total activities and 92.91% fewer mandatory activities than individuals who work regularly. Retirees and pensioners, on average, perform 47.17% fewer total activities and 92.60% fewer mandatory activities than the reference category. People unemployed participate in 51.82% fewer total activities and 83.66% fewer mandatory activities than regular workers. Individuals who have never worked are also negatively associated with the total (-70.62%) and mandatory (-95.84%) activities compared to those who work. Housewives participate in 43.89% fewer total activities and 79.03% fewer mandatory activities than those who have regular work, on average. Students also participate in fewer total (-38.14%) and compulsory (-59.30%) activities than people who work.

In the discretionary activities model, Retired and pensioners, people without work and housewives present a higher level of participation than those who work regularly and study. Retirees and pensioners participate in 64.10% more activities, on average, than the reference category. People unemployed perform 38.66% more discretionary activities than those with regular work. On the other hand, Housewives have a level of participation

83.28% higher, on average, than people who regularly work outside the home. Finally, the category of students participates in 18.89% fewer discretionary activities than the reference category.

People who live in socially vulnerable regions participate in fewer total, mandatory and discretionary activities. The level of statistical significance of this variable was 99% for the total activities model, 95% for mandatory activities and 99.9% for discretionary activities. People living in these regions perform 5.46% fewer total activities, 8.39% fewer mandatory activities and 22.50% fewer discretionary activities, on average, than individuals living in regions that are not socially vulnerable. This finding is in line with TRSE literature (Lucas et al., 2011; Ureta, 2008).

The educational level was statistically significant at the 99.9% level for the total and discretionary activities model. The lower the level of education, the fewer total and discretionary activities the individual engages in. Compared to the reference category (Higher Education Complete), individuals in the category High School Complete / Higher Education Incomplete participate in 12.94% fewer activities, those with Complete Elementary II/ High School Incomplete 20.02% fewer, those with Elementary II Complete/ High School Incomplete 22.91% fewer and those who are illiterate or with Incomplete Primary 30.75% fewer. For the discretionary activities model, individuals in the categories Non-Literate/Incomplete Primary I, Elementary I Complete / Elementary II Incomplete, Elementary II Complete / High School Incomplete and High School Complete / Higher Education Incomplete participate in 50.94%, 40.92%, 40.26% and 32.78% fewer activities, respectively, than those in Higher Education Complete category. In the mandatory activities model, Non-Literate/Incomplete Primary I, Elementary II Complete/High School Incomplete and High School Complete / Higher Education Incomplete have an average participation rate, 21.13%, 13.49% and 8.68% fewer than those with Higher Education Complete. These results are consistent with the TRSE literature, which indicates that illiterate or cognitively impaired individuals often find using public transport confusing (Denmark, 1998). It is worth noting that low educational level is correlated with the category of youth and low-income adults.

The population density variable was significant at the 95% level for the total and discretionary activity models. Population density is positively associated with activity participation, indicating that individuals participate in more activities in denser locations. The density change in 1000 inhabitants per km^2 is associated with an increase of 0.10% in total activities and 0.26% in discretionary activities. A one standard deviation increase in density (11.06) is associated with a 1.16% increase in participation in total activities and by 2.93% in discretionary activities, on average. Despite the small magnitude, this result is in line with other studies (Cheng *et al.*, 2019; Merlin, 2015). The literature suggests that denser locations make the urban environment livelier and more attractive to undertake trips on foot (Ewing *et al.*, 1996; Ma *et al.*, 2018). In addition, denser places may be associated with less need to use private vehicles to carry out activities.

4.5.2 Accessibility-Activity Participation Relationship

The relationships between accessibility measured by the cumulative opportunities measure (CUM) with a 90-minute threshold and the total, mandatory and discretionary activities were analysed with a maximum likelihood estimation of a Poisson regression model. An instrumental variable strategy was used to overcome any possible endogeneity issue caused by omitted variable and, therefore, infer causality between accessibility and activity participation. Although the cumulative opportunities measure of accessibility does not capture several of the nuances that may influence individuals' ability to engage in activities, it still has a causal effect on activity participation. It means that higher levels of accessibility cause greater activity participation, regardless of the type of activity.

The three estimated models (Table 4.17, 4.18 and 4.19 indicate that accessibility is highly significant, at least at the 99% significance level. However, the impact accessibility is not the same for the three categories of activities. The increment of one percentage point in the number of jobs that the individual can access by public transport within 90 minutes causes a 0.48% increase in the total activities carried out, 1.06% in the mandatory activities, and 0.73% in the number of discretionary activities, on average. On average, one standard deviation on accessibility (0.24) increases 11.49% in total activities, 25.51% in mandatory activities, and 17.61% in discretionary activities.

Although the relative impact of accessibility is higher for mandatory-type activities, the absolute impact on the number of activities is higher for the total activities category, followed by mandatory and discretionary activities. This result goes against many studies on the relationship between accessibility and trip making, which suggest that trip making for discretionary purposes are more elastic than for mandatory reasons. Nevertheless, the sample characteristics may be influencing the results. The São Paulo OD Survey register only trips made during weekdays, when the proportion of activities for discretionary purpose is limited. In this sense, it may be possible that the impact of accessibility on discretionary activities is greater than we found.

The findings suggest that greater accessibility levels cause greater participation in mandatory activities. Considering that individuals participate in only one employment activity per day, it is possible that as an individual's accessibility level increases, individuals may move from 0 to 1 mandatory activity performed. In this way, we can speculate that higher levels of accessibility may be associated with a higher probability of getting a job. This hypothesis was confirmed by Bastiaanssen *et al.* (2021) in the Great Britain context. Likewise, we can speculate that individuals with low levels of accessibility may have limited access to education. In other words, low levels of accessibility can considerably restrict an individual's life chances.

Figure 4.25 shows the relationship between accessibility and activity participation. Although the curve shape of the models fit the activity participation distribution very well, it fails to capture the diminishing effect on participation for the highest levels of accessibility suggested by Martens (2016a) and Allen and Farber (2020). According to our model, participation should increase exponentially when accessibility increases, which contradicts the widely held belief in the literature that improvements in the low end of the accessibility range should result in the greatest increases in participation. This finding is similar to Fransen *et al.* (2018a)'s findings for the accessibility-activity participation curve.

Some possible explanations for the shape of the curve found can be raised. Even though Figure 4.25 suggest an exponential relationship between accessibility and participation in activities, the slope increases at a small rate, fitting almost a linear relationship between the variables. This may suggest that accessibility and activity participation have a linear relationship, as assumed by most of the studies about the topic. Another possible explanation is that the curve shape that we found depicts only the lower part of the accessibility spectrum of the Allen and Farber (2020) sigmoid curve. In other words, even at the highest levels of accessibility in our study context, this level was not sufficient to

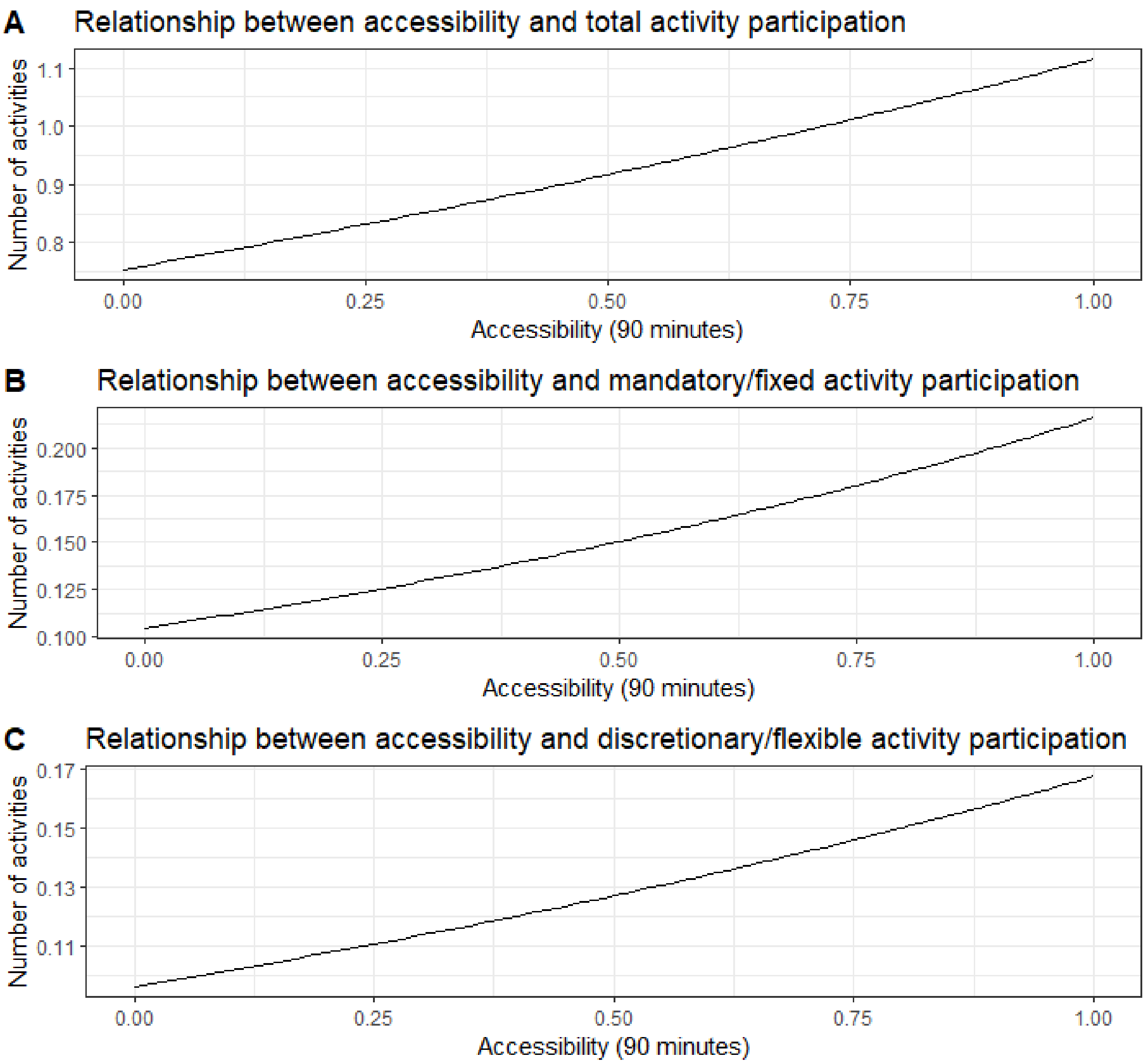


Figure 4.25: The shape of accessibility-activity participation relationship

reach the inflexion point of the sigmoid curve. It is worth noting that the city of São Paulo is considerably larger than other cities in which similar studies have been carried out. A third explanation for our results may be the characteristics of the sample. The São Paulo OD survey collects data for a 24-hour period. Perhaps a more apparent pattern of a sigmoid curve or a curve with diminishing gains in activity participation would be obtained using a more extended time window, such as a week.

Finally, the individuals' gains from greater accessibility levels may be underestimated. Individuals may be interested not in the number of activities they participate in but in the quality of those activities. It is unlikely that individuals will participate in more than one work or education activity because of increased levels of accessibility. However, this individual may get a better-paid job or access better quality education because of higher levels of accessibility. As a result, all else being equal, a better level of accessibility is likely to allow people to obtain more benefits from participating in activities.

4.6 Conclusions

Most of the transport equity and TRSE studies assume that increasing accessibility levels lead to increased activity participation and, therefore, a social exclusion reduction. Although this assumption makes sense from the theoretical point of view, popular accessibility measures applied in practice account only for some of the components that shape an individual's possibilities of participation. Additionally, previous studies investigating the accessibility-activity participation relationship were inconclusive, indicating that policy interventions in terms of accessibility may lead to misleading results. The empirical evidence available in the literature are merely correlational and fail to establish a causal effect of accessibility on activity participation. Based on the findings of earlier studies, the validity and intensity of this relationship may be context-specific; however, studies conducted in the Global South context are almost non-existent. Also, most of the previous studies using location-based accessibility measures adopted an aggregate approach, failing to control for heterogeneity of interpersonal characteristics adequately.

This chapter has provided a more in-depth understanding of the relationship between accessibility and participation in activities. A Poisson regression model associated with an instrumental variable identification strategy was used to assess the causal effect between accessibility and participation in total, mandatory and discretionary activities in the city of São Paulo. The accessibility measure CUM was used to measure the individuals' levels of accessibility. The choice of such measure was not by chance. CUM is one of the most used accessibility measures in practice, and it is simple to calculate and interpret. These are essential features in a Global South context, where data limitations and low skilled technical staff are common. Also, CUM has some theoretical advantages from the TRSE point of view since it makes no assumptions about how people perceive the quality of opportunities or transportation costs. We adopt a disaggregated approach to control for individuals' sociodemographics characteristics properly.

The three models showed a highly significant, strong correlation between an individual's accessibility level and his/her actual participation in total, mandatory and discretionary activities. We tested four different time thresholds and found that the one that best explains the dependent variable variability is the 90-minute. Based on our results, we argue that low accessibility levels may severely restrict individuals' life chances. It indicates that accessibility, even when accounting only for transport and land use components, such as CUM measure, is critical in enhancing individuals' capabilities. We also suggest that individuals may be interested in the number of activities they participate in and the quality of those activities. In this sense, the gains provided by accessibility improvements may be much higher than those estimated.

The three models that we proposed fit the distribution of the dependent variables very well. However, the models failed to capture the diminishing participation for individuals with high accessibility levels. We speculate three possible explanations for our findings. First, accessibility and activity participation may have a linear relationship. Second, the curve shape that we found depicts only the lower part of a sigmoid curve, meaning that our sample's maximum level of accessibility was insufficient to reach the sigmoid's inflexion point. Third, a 24-hour data collection period is too short for revealing a sigmoid or a curve with diminishing gains in activity participation shape.

Although we cannot infer causality between the relationship between activity participation and socioeconomic and locational variables, our results proved consistent with the TRSE literature. Only two variables had divergent results from the theory: gender and race. The gender variable does not present statistical significance to explain participation in all three categories of activities. The gender variable was no longer statistically significant after introducing the family status variable in the models. It may indicate that what impacts activity participation is not necessarily the gender but the family status. Future investigations are necessary to resolve this issue. Also, further research using proper metrics to capture difficulties in activity participation due to an individual's race is needed.

The magnitude of accessibility effect on activity participation was comparable to the effect of the socio-demographic and locational variables. This finding reinforces the narrative that TRSE is not merely a spatial phenomenon but also an individual one. While transport and land use resources play a crucial role in enabling individuals to participate in the activities they desire, individual characteristics are equally important to recognise these resources and convert them into actual participation. In this sense, while macro-level impact assessments of transport interventions are valid using place-based and aggregate accessibility measures such as CUM, identifying individuals at risk of TRSE requires a bottom-up approach focused on individual's characteristics.

Although this chapter is an improvement over previous studies in this field, further research questions may stem from the present chapter. A longer time horizon in data collection may also capture fluctuations in activity participation patterns. Including weekend trip making information in OD Survey may help better estimate the relationship between accessibility and discretionary activity participation. Additionally, we recommend the introduction of race-related variables in OD surveys to capture activity participation inequality due to race issues. We used an accessibility measure that accounts only for formal jobs and the travel time by public transport. Adopting an accessibility approach that differentiates between opportunities type and transport modes could provide different insights about the impact of accessibility on participation.

We have provided causal evidence of a relationship between accessibility and activity participation. However, there is still much debate in the literature about whether this relationship is valid. Therefore, more evidence on the validity of this relationship is needed, especially in the context of the Global South. Such evidence must use identification strategies to ensure the validity of the cause-and-effect relationship between accessibility and activity participation. We have used an instrumental variable identification strategy; however, this is one of the least robust methods for inferring causality. Randomized experiments are desirable to obtain more robust results. Also, a more in-depth investigation about how accessibility levels may restrict an individual's life chances are desirable.

Furthermore, much of the theoretical and empirical TRSE work assumes that many of the socio-demographic variables discussed here cause TRSE. However, this relationship may be bidirectional or in the opposite direction, that social exclusion causes social disadvantage. Thus, studies concerned with the cause-effect relationship between sociodemographic variables and the level of participation in activities are also desirable for a better understanding of the phenomenon of TRSE.

Chapter 5

Conclusions

5.1 Thesis Summary

The contributions of this dissertation to state of the art is threefold. The first contribution is establishing a robust theoretical framework for assessing the phenomenon of transport-related social exclusion. Such a framework provides a detailed overview of how individuals may be prevented from travelling and accessing valued opportunities and how this may lead to ten different forms of transport-related social exclusion. The theoretical framework suggests articulating the accessibility concept with the Sen's Capabilities Approach. Understanding the accessibility concept as a human capability contributes to removing the transport policy focus on the distribution of resources. It acknowledges that assessing how well off an individual is based on the transport and land use resources they have access to is superficial and can often lead to distorted distributional outcomes. The idea of accessibility as human capability recognises the diversity of individual needs and preferences and their respective limitations in converting those resources into access and participation in activities they value. This approach suggests that "a place is not just 'more' or 'less' accessible, but accessible relative to people in all their different circumstances "(Farrington, 2007, p.320).

By sharing sufficientarianist ideals, the notion of accessibility as human capability combines accessibility needs with the idea of social rights to the extent that a minimum level of accessibility is required to meet an individual's basic needs. The incorporation of this idea by policymakers may contribute to implementing a normative criterion that can guarantee a minimum standard of accessibility for the entire population and thus mitigate transport-related social exclusion. In addition, defining minimum accessibility thresholds can help policymakers understand how much accessibility is needed to meet the minimum level of accessibility for as many people as possible.

The second contribution of the dissertation was to provide an analytical framework for assessing the adherence of accessibility measures to the theoretical framework provided. Besides considering the theoretical consistency of the accessibility measures, the analytical framework also incorporates aspects related to the usability and interpretability of the measures. There is a trend among more recent studies on accessibility to develop increasingly complex and detailed accessibility. However, most transportation planning agencies, especially in Global South cities, do not have the necessary data to input into the models, equipment powerful enough for their calculation or even staff technically capable of performing the calculations. Moreover, the complexity of calculating these measures often goes hand in hand with interpretability and communicability difficulties, which hinders the communication of the policies to the general audience. In this sense, researchers should be concerned with developing theoretically consistent accessibility measures without losing sight of their practical applicability.

The dissertation found that not all accessibility measures are suitable for assessing TRSE. Also, it was identified that there is no accessibility measure capable of capturing all the elements that may influence the ability of individuals to access and participate in activities. As pointed out by the theoretical framework provided in chapter 2, the idea of accessibility as a human capability is much more complex and multifaceted than those applied in transportation research. No matter how complex and detailed the accessibility measure is, many aspects that may restrict individuals' opportunities set, such as fear, educational level, physical condition, social status, discrimination, and prejudice, are hard to measure. In this sense, researchers and planners should at least avoid existing measures that may theoretically conflict with the idea of accessibility as a human capability. Public policies aimed at tackling TRSE should be founded on the concept of accessibility as a human capability, with strong sufficientarian principles to prioritise and ensure a minimal level of capabilities for those in accessibility poverty.

Researchers and planners should be aware of the consistency of the selected accessibility measure assumptions with the planning objectives sought. This is a critical aspect of accessibility planning since the selected accessibility measure can considerably influence the distributive outcomes of a given policy and suggest misleading interventions for the investigated issue. Three (CUM, NUM, and $CFOS$) among the 24 accessibility measures assessed stood out as the most suitable to assess the risk of transport-related social exclusion. However, selecting the best one among them will vary according to the size of the study area, the type of activity to be assessed, and the amount of data and computational power available. Lastly, it is worth noting that dismissing the other accessibility measures does not mean they are worthless; they are simply less adequate to assess TRSE risk than CUM, NUM and $CFOS$.

The third contribution of the dissertation was to infer a causal relationship between accessibility measured by CUM and activity participation levels. No work was found to provide evidence of a causal relationship of accessibility on activity participation level. All the papers reviewed on the subject in this dissertation adopted a correlational approach. Furthermore, only two of the 33 reviewed were from Global South countries, none of which were in a South American context. In this sense, this seems to be a relevant contribution to the state of the art of transport-related social exclusion research. These findings may contribute at least to some extent to the debate about accessibility-activity participation.

The findings suggest that a greater level of accessibility (measured by CUM) causes greater participation in total, mandatory and discretionary activities. It is argued that low accessibility levels may be associated with a higher probability of getting a job or that individuals with low accessibility levels may have limited access to education. Simply put, low levels of accessibility can severely restrict an individual's life chances and, consequently, put him/her at risk of social exclusion.

It is also possible that the impacts of accessibility on the level of participation are even greater than those estimated. The sample data used in the study case is limited to trips made during weekdays, which may underestimate participation in discretionary activities. Also, the gains from increased accessibility are quantitative and qualitative. Individuals with better accessibility may not necessarily participate in more activities but in activities that better fit their preferences.

Finally,

5.2 Reflections on Emerging Issues and Future Research

Some questions emerged during the research that open up potential future research avenues. Most of the TRSE research fails to differentiate between the causal factors behind TRSE and its social outcomes. Many of the TRSE factors are both the cause and result of TRSE. Almost none of the empirical studies reviewed for this dissertation set out to establish causal inference characteristics associated with the risk of TRSE and the level of participation. In this sense, more empirical studies that evaluate the causal link between characteristics of TRSE and the level of participation are highly desired to develop more successful inclusive transport policies.

There are some concerns about defining the minimum level of accessibility suggested by the idea of accessibility as a human capability. Below what threshold does it imply a problem that legitimises or suggests the need for policy interventions? This practical and philosophical issue in the TRSE literature was not still addressed. It is advocated that the definition of the sufficient level is context-specific. The relevant activities that the minimum level of accessibility should be provided will vary according to that society's political, economic and social norms. However, further research is needed to develop methodologies to define the sufficient level of accessibility in each society. It is expected that the definition of the minimum accessibility threshold occurs explicitly through an open and participatory political process. This decision should not be taken exclusively by technicians or taken behind closed doors.

According to the analytical framework to assess the suitability of accessibility measures to evaluate the risk of TRSE, three accessibility measures were selected as the most recommended. Despite the value of this theoretical finding, more empirical evidence applying the selected measures is needed to validate it. Furthermore, all accessibility measures assessed by the analytical framework focused on macro and mesoscale and did not cover local aspects such as walkability and built environment features. In this sense, more theoretical and empirical research about these measures' suitability to assess TRSE is highly desirable. Also, a better understanding of the TRSE phenomenon may be achieved if the combined application of macro, meso and local scale accessibility measures.

The dissertation findings suggest that greater accessibility levels, as measured by

CUM, causes greater activity participation. Nevertheless, the evidence provided by the dissertation does not settle the discussion. Further research is needed to study the accessibility-activity participation relationship from both theoretical and empirical perspectives. More measures of accessibility should be tested and in more different contexts, especially in developing countries where social exclusion can assume different forms from cities in the Global North. It is expected that future research on this topic to be concerned with investigating the causal relationship between both variables and, preferably, using more robust identification strategies than instrumental variables. Such results will be of extreme value for developing more inclusive transport policies.

Furthermore, further in-depth studies on the qualitative gains generated by accessibility are suggested. In the dissertation, only the quantitative aspect of activity participation was addressed. However, the qualitative gains may be even greater than the quantitative ones. Qualitative gains include not only accessing activities that best fit the individual's preferences but also the gains from broadening the range of activities in which the individual can potentially participate.

Finally, the dissertation focused exclusively on the aspects related to social exclusion related to transport. From an exclusively social perspective, more travel is always beneficial, as it means participation in more activities. However, from a sustainable mobility point of view, it is possible to have negative environmental and economic impacts depending on the conditions under which these trips occur. Thus, future research should broaden the focus and consider the interaction of the social aspect of sustainability with the environmental and economic aspects associated with increased accessibility.

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Appendix A

Summary of the Qualitative Assessment of the 24 accessibility measures

Table A.1: Qualitative assessment of the 24 accessibility measures according to criteria 1 to 6

Measure	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6
$DMIN$	Access to activities	Point-based or zone-based	No	Yes (Distance)	Not much. Sensitive only to the spatial distribution of nearby activities.	Only captures variations in service level (not travel time) of transport throughout the day if measured multiple times. It does not capture the availability of opportunities throughout the day.
$TMIN$	Access to activities	Point-based or zone-based	No	Yes (Time)	Not much. Sensitive only to the spatial distribution of nearby activities.	It requires multiple measurements.
$DMIN_{Trans}$	Access to activities indirectly	Point-based or zone-based	No	No	No	It does not capture the fluctuation of travel time and opportunity availability throughout the day.
$TMIN_{Trans}$	Access to activities indirectly	Point-based or zone-based	No	No	No	It does not capture the fluctuation of travel time and opportunity availability throughout the day.
$DCBD$	Access to activities indirectly	Point-based or zone-based	No	Yes (Distance)	No	It does not capture the fluctuation of travel time and opportunity availability throughout the day.
BT	Access to activities	Zone-based	No	Yes (Time). It can be adapted for distance.	Yes, consider all activities as equals. It incorporates competition.	It requires multiple measurements.
$CONT$	Access to activities	Zone-based	No	No	Yes, it considers the activities as equal, being able to adjust the attractiveness according to the supply level.	It does not capture fluctuation in travel time throughout the day. Requires multiple measurements to incorporate fluctuation in activity availability throughout the day.
$PTPR$	Access to activities	Zone-based	No	No	Yes, it considers the activities as equal, being able to adjust the attractiveness according to the level of supply.	It does not capture fluctuation in travel time throughout the day. Requires multiple measurements to incorporate fluctuation in activity availability throughout the day.

Table A.1: Qualitative assessment of the 24 accessibility measures according to criteria 1 to 6

Measure	**Criterion 1**	**Criterion 2**	**Criterion 3**	**Criterion 4**	**Criterion 5**	**Criterion 6**
$GRAV$	Access to activities	Point-based or zone-based	No. It makes assumptions regarding how individuals perceive travel time and the attractiveness of activities.	Yes (Distance, Time or Monetary cost).	Yes. It articulates differences in the quality of activities employing a composite index. Makes assumptions regarding how individuals perceive the attractiveness of activities.	It requires multiple measurements.
$GRAV_{Comp}$	Access to activities	Zone-based	No. It makes assumptions regarding how individuals perceive travel time and the attractiveness of activities.	Yes (Distance, Time or Monetary cost).	Yes, it considers all activities as equals. It incorporates competition.	It requires multiple measurements.
CUM	Access to activities	Point-based or zone-based	No	Yes (Distance, Time or Monetary cost). Not very sensitive to variations in travel time/distance. Allows monetary cost to be input without relying on observed travel behavior.	Yes, consider all activities as equals.	It requires multiple measurements.
CUM_{Comp}	Access to activities	Zone-based	No	Yes (Distance, Time or Monetary cost). Not very sensitive to variations in travel time/distance. Allows monetary cost to be input without relying on observed travel behavior.	Yes, consider all activities as equals. It incorporates competition.	It requires multiple measurements.

Table A.1: Qualitative assessment of the 24 accessibility measures according to criteria 1 to 6

Measure	**Criterion 1**	**Criterion 2**	**Criterion 3**	**Criterion 4**	**Criterion 5**	**Criterion 6**
$UTIL$	Access to activities	(Group of) Person-based	Partially. It makes assumptions about individual perceptions of transport impedance based on the generalized cost of the shortest path. For opportunities, it makes assumptions about individual perceptions in an aggregated way. It allows the incorporation of other individual characteristics.	Yes (Distance, Time or Monetary cost). It is able to calculate for all modes of transport at once.	Yes, it varies according to model specifications.	It requires multiple measurements.
$VSTP$	Access to activities indirectly	Person-based	Yes	Yes (Time)	Yes, only mandatory activities.	Yes
$APPA$	Access to activities indirectly	Person-based	Yes	Yes (Time)	Yes, only mandatory activities.	Yes
LEN	Access to activities indirectly	Person-based	Yes	Yes (Time)	Yes, only mandatory activities.	Yes
NUM	Access to activities.	Person-based	Yes	Yes (Time)	Yes, consider all activities as equals.	Yes
$CFOS$	Access to activities	Person-based	Yes. It incorporates the individuals' cognitive constraints.	Yes (Time)	Yes, consider all activities as equals.	Yes
$NUMD$	Access to activities	Person-based	Yes. It makes assumptions regarding how individuals evaluate travel time.	Yes (Time)	Yes, consider all activities as equals.	Yes

Table A.1: Qualitative assessment of the 24 accessibility measures according to criteria 1 to 6

Measure	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6
WA	Access to activities	Person-based	Yes. It makes assumptions regarding how individuals evaluate activities attractiveness.	Yes (Time)	Yes. It articulates differences in the quality of activities using a composite index. Makes assumptions regarding how individuals perceive the attractiveness of activities.	Yes
DUR	Access to activities indirectly	Person-based	Yes	Yes (Time)	Yes, only mandatory activities.	Yes
$BAGG$	Access to activities	Person-based	Yes. It makes assumptions regarding how individuals evaluate travel time and the attractiveness of activities.	Yes (Time)	Yes. It articulates differences in the quality of activities employing a composite index. Makes assumptions regarding how individuals perceive the attractiveness of activities.	Yes
$BMAX$	Access to activities	Person-based	Yes. It makes assumptions regarding how individuals evaluate travel time and the attractiveness of activities.	Yes (Time)	Yes. It articulates differences in quality of activities employing composite index. Makes assumptions regarding how individuals perceive the attractiveness of activities. Not very sensitive to variation in quantity and quality of activities.	Yes
$BTTRANS$	Access to activities	Person-based	Yes. It makes assumptions regarding how individuals evaluate travel time and the attractiveness of activities.	Yes (Time)	Yes. It articulates differences in the quality of activities employing composite index. Makes assumptions regarding how individuals perceive the attractiveness of activities. Not very sensitive to variation in quantity and quality of activities.	Yes

Table A.2: Qualitative assessment of the 24 accessibility measures according to criteria 7 to 12

Measure	**Criterion 7**	**Criterion 8**	**Criterion 9**	**Criterion 10**	**Criterion 11**	**Criterion 12**
$DMIN$	Single trips	No	It does not replicate observed behavioral bias	It adopts a maximization strategy	It is easily operationalized. It only requires information from the activities closest to the origin.	Very easy to communicate and interpret.
$TMIN$	Single trips	No	It does not replicate observed behavioral bias	It adopts a maximization strategy	It is easily operationalized. It only requires information from the activities closest to the origin.	Very easy to communicate and interpret.
$DMIN_{Trans}$	It does not allow to evaluate trips to the final destination, only to public transport	No	It does not replicate observed behavioral bias	It adopts a maximization strategy	It is easily operationalized. It only requires information from the activities closest to the origin.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.
$TMIN_{Trans}$	It does not allow to evaluate trips to the final destination, only to public transport	No	It does not replicate observed behavioral bias	It adopts a maximization strategy	It is easily operationalized. It only requires information from the activities closest to the origin.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.
$DCBD$	Single trips	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	It is easily operationalized. It requires only the information regarding the coordinates of the city centre. It can be calculated in one go.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.
BT	Single trips	No	It does not replicate observed behavioral bias	It adopts a maximization strategy	It is easily operationalized. It only requires data on activities' quantity, and spatial distribution, and travel time between origins and destinations.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.
$CONT$	It does not allow to evaluate trips	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	It is easily operationalized with basic GIS knowledge. They only require data on the distribution of activities.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.

Table A.2: Qualitative assessment of the 24 accessibility measures according to criteria 7 to 12

Measure	**Criterion 7**	**Criterion 8**	**Criterion 9**	**Criterion 10**	**Criterion 11**	**Criterion 12**
$PTPR$	It does not allow to evaluate trips	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	It is easily operationalized with basic GIS knowledge. They only require data on the distribution of activities.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.
$GRAV$	Single trips	No	If calibration of the impedance function occurs based on travel behavior, it replicates observed behavioral biases.	It is not based on a maximization strategy.	Medium operational difficulty. Requires data on the quantity, quality and spatial distribution of activities, and information from the OD survey to calibrate the impedance function parameter.	High difficulty of understanding. The introduction of the attractiveness of activities and the impedance function prevents a straightforward understanding of the result. The values can be normalised within the range of the results found in the region to facilitate the interpretation of this measure.
$GRAV_{Comp}$	Single trips	No	If calibration of the impedance function occurs based on travel behavior, it replicates observed behavioral biases.	It is not based on a maximization strategy.	High difficulty of operationalization. Requires OD survey data, the number of people in each zone, the proportion of people seeking the assessed type of opportunity (demand) and the number of opportunities (supply) in each of the zones. It requires the definition and calibration of two impedance functions.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.
CUM	Single trips	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	It is easily operationalized. It only requires data on activities' quantity and spatial distribution, and travel time between origins and destinations.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.
CUM_{Comp}	Single trips	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	Medium operational difficulty. It requires OD survey data, the number of people in each zone, the proportion of people seeking the evaluated opportunity (demand), and the number of opportunities (supply) in each zone.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.

Table A.2: Qualitative assessment of the 24 accessibility measures according to criteria 7 to 12

Measure	**Criterion 7**	**Criterion 8**	**Criterion 9**	**Criterion 10**	**Criterion 11**	**Criterion 12**
$UTIL$	Single trips	Yes	It does replicate observed travel behavior	It adopts a maximization strategy	Great difficulty of operationalization. The definition of the logsum function and the calculation of the measure are quite complex. Simplifications like clustering or random selection are needed to handle computational costs. There are objections to using a random selection of alternatives due to spatial autocorrelation and Interdependence of Irrelevant Alternatives (IIE) concerns.	Very high difficulty in communicating and interpretating. To be clearly explained requires references to complex theories. Impossible to compare different utility functions unless transformed into monetary costs. No physical/spatial interpretation of the measure.
$VSTP$	Single trips and trip chaining	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	Great difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to the application due to the requirement of specific GIS packages. Operationalizable models are scarce. Generally, make simplifications concerning the transport component.	Medium difficulty in communicating and interpreting. Results can be interpreted straightforwardly and in absolute units. Requires reference to space-time theory to be explained.
$APPA$	Single trips and trip chaining	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	Great difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to the application due to the requirement of specific GIS packages. Operationalizable models are scarce. Generally, make simplifications concerning the transport component.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.

Table A.2: Qualitative assessment of the 24 accessibility measures according to criteria 7 to 12

Measure	**Criterion 7**	**Criterion 8**	**Criterion 9**	**Criterion 10**	**Criterion 11**	**Criterion 12**
LEN	Single trips and trip chaining	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	Great difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to the application due to the requirement of specific GIS packages. Operationalizable models are scarce. Generally, make simplifications concerning the transport component.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.
NUM	Single trips and trip chaining	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	Great difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to the application due to the requirement of specific GIS packages. Operationalizable models are scarce. Generally, make simplifications concerning the transport component.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.
$CFOS$	Single trips and trip chaining	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	Great difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to application due to the requirement of specific GIS packages. There is a scarcity of operationalizable models. Generally, make simplifications in relation to the transport component.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.

Table A.2: Qualitative assessment of the 24 accessibility measures according to criteria 7 to 12

Measure	**Criterion 7**	**Criterion 8**	**Criterion 9**	**Criterion 10**	**Criterion 11**	**Criterion 12**
$NUMD$	Single trips and trip chaining	No	If calibration of the impedance function occurs based on travel behavior, it replicates observed behavioral biases.	It is not based on a maximization strategy.	Very high difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to the application due to the requirement of specific GIS packages. Operationalizable models are scarce. Generally, make simplifications concerning the transport component. It requires parameter setting and calibration of the decay function.	Medium difficulty in communication and interpretation. Weighting by impedance function hinders a straightforward interpretation of the measure.
WA	Single trips and trip chaining	No	It does not replicate observed behavioral bias	It is not based on a maximization strategy.	Great difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to the application due to the requirement of specific GIS packages. Operationalizable models are scarce. Generally, make simplifications concerning the transport component. It requires data on the attractiveness of activities.	Medium difficulty in communication and interpretation. Weighting by impedance function hinders a straightforward interpretation of the measure.
DUR	Single trips and trip chaining	No	It does not replicate observed behavioral bias	It adopts a maximization strategy	Great difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to the application due to the requirement of specific GIS packages. Operationalizable models are scarce. Generally, make simplifications concerning the transport component.	Very easy to communicate and interpret. Results can be interpreted straightforwardly and in absolute units.

Table A.2: Qualitative assessment of the 24 accessibility measures according to criteria 7 to 12

Measure	**Criterion 7**	**Criterion 8**	**Criterion 9**	**Criterion 10**	**Criterion 11**	**Criterion 12**
$BAGG$	Single trips and trip chaining	Yes	If calibration of the impedance function occurs based on travel behavior, it replicates observed behavioral biases.	It is not based on a maximization strategy.	Great difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to the application due to the requirement of specific GIS packages. Operationalizable models are scarce. Generally, make simplifications concerning the transport component. It requires parameter setting and calibration of the decay function.	Very high difficulty of communication and interpretation. Weighting by impedance function and attractivity increase complexity. To be clearly explained requires making references to complex theories. Impossible to compare with measures that adopt different utility functions.
$BMAX$	Single trips and trip chaining	Yes	If calibration of the impedance function occurs based on travel behavior, it replicates observed behavioral biases.	It adopts a maximization strategy	Great difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to the application due to the requirement of specific GIS packages. Operationalizable models are scarce. Generally, make simplifications concerning the transport component.	Very high difficulty of communication and interpretation. Weighting by impedance function and attractivity increase complexity. To be clearly explained requires making references to complex theories. Impossible to compare with measures that adopt different utility functions.
$BTTRANS$	Single trips and trip chaining	Yes	If calibration of the impedance function occurs based on travel behavior, it replicates observed behavioral biases.	It adopts a maximization strategy	Great difficulty of operationalization. It requires high computational power and detailed data that is difficult to collect from the individuals' activity diaries. It is limited to small shares of the population. There are financial barriers to the application due to the requirement of specific GIS packages. Operationalizable models are scarce. Generally, make simplifications concerning the transport component. It also faces difficulties in the operationalization of the UTIL measure.	Very high difficulty of communication and interpretation. Weighting by impedance function and attractivity increase complexity. To be clearly explained requires making references to complex theories. Impossible to compare with measures that adopt different utility functions.

Appendix B

Models before the IV introduction

Table B.1: Total activities model before the introduction of the IV

Total activities model before the introduction of instrumental variable (n = 47167)					
Model summary					
	R^2 McFadden			0.0855	
	AIC			115552.6	
	Log pseudolikelihood			-57740.294	
Independent Variable	**IRR**	**Robust Std. Error**	**Z**	**P-value**	
Accessibility (90 minutes)	1.4790	0.0622	6.29	0.000	***
Family per capita income (in thousand reais)	1.0472	0.0046	10.51	0.000	***
(Family per capita income (in thousand reais)) ^ 2	0.9985	0.0003	-5.66	0.000	***
Age	1.0104	0.0016	6.54	0.000	***
(Age) ^ 2	0.9998	0.0000	-9.74	0.000	***
Family per capita private vehicles	1.0784	0.0146	5.57	0.000	***
Gender (reference "Male")					
Female	0.9961	0.0082	-0.47	0.637	
Number of people in the family	1.1324	0.0114	12.30	0.000	***
(Number of people in the family) ^ 2	0.9917	0.0012	-6.85	0.000	***
Proportion of self-declared black population in the region	0.9126	0.0330	-2.53	0.011	*
Study Status (reference "No")					
Primary/Elementary	1.8772	0.0545	21.70	0.000	***
Secondary/Middle	1.8066	0.0448	23.85	0.000	***
Higher/University	1.4909	0.0211	28.20	0.000	***
Other	1.4217	0.0417	11.98	0.000	***
Employment status (reference "Has a regular job")					
Does odd-jobs	0.7527	0.0161	-13.29	0.000	***
On sick leave	0.3452	0.0311	-11.81	0.000	***
Retired/Pensioner	0.5286	0.0110	-30.73	0.000	***
Unemployed	0.5014	0.0143	-24.21	0.000	***
Never worked	0.2809	0.0400	-8.92	0.000	***
Housewife	0.5743	0.0187	-17.07	0.000	***
Student	0.6314	0.0155	-18.70	0.000	***
Live in a high social vulnerability region (reference "No")					
Yes	0.9431	0.0145	-3.81	0.000	***
Level of Education (reference "Higher Education Complete")					
Non-Literate/Incomplete Primary	0.7137	0.0172	-13.99	0.000	***
Elementary I Complete/Incomplete Elementary II	0.7826	0.0157	-12.19	0.000	***
Elementary II Completo/High School Incompleto	0.8073	0.0143	-12.06	0.000	***

High School Complete / Higher Education Incomplete	0.8835	0.0098	-11.19	0.000	***
Individual income (reference "Did not answer")					
Yes	1.0914	0.0096	9.97	0.000	***
No	0.9513	0.0230	-2.06	0.039	*
Populational Density	1.0017	0.0004	4.87	0.000	***
Family status (reference "Responsible person")					
Spouse / Partner	0.8823	0.0103	-10.68	0.000	***
Child / Stepchild	0.7564	0.0100	-21.12	0.000	***
Other Relative	0.6839	0.0125	-20.87	0.000	***
Other Resident	0.7848	0.0275	-6.92	0.000	***
Resident Employee	0.2697	0.0288	-12.28	0.000	***
Relative of Resident Employee	0.4510	0.1913	-1.88	0.060	.
Constant	0.8778	0.0427	-2.68	0.007	**

Note: (.) p <0.1; (*) p <0.5; (**) p <0.01; (***) p <0.001

Table B.2: Mandatory/Fixed activities model before the introduction of IV

Mandatory/Fixed activities model before the introduction of instrumental variable (n = 47167)					
Model summary					
		R² McFadden		0.192	
		AIC		87760.57	
		Log pseudolikelihood		-43847.284	
Independent Variable	**IRR**	**Robust Std. Error**	**Z**	**P-value**	
Accesibility (90 minutes)	1.0908	0.0271	3.4900	0.0000	***
Family per capita income (in thousand reais)	1.0132	0.0022	5.9300	0.0000	***
Age	1.0112	0.0020	5.5500	0.0000	***
(Age) ^ 2	0.9998	0.0000	-9.3900	0.0000	***
Family per capita private vehicles	1.0611	0.0145	4.3400	0.0000	***
Gender (reference "Male")					
Female	0.9758	0.0082	-2.9200	0.0030	
Number of people in the family	1.2671	0.0162	18.5700	0.0000	***
(Number of people in the family) ^ 2	0.9817	0.0016	-11.4000	0.0000	***
Proportion of self-declared black population in the region	0.8593	0.0318	-4.1000	0.0000	***
Study Status (reference "No")					
Primary/Elementary	1.9530	0.0609	21.4700	0.0000	***
Secondary/Middle	1.9135	0.0500	24.8400	0.0000	***
Higher/University	1.6305	0.0224	35.5900	0.0000	***
Other	1.5080	0.0452	13.7000	0.0000	***
Employment status (reference "Has a regular job")					
Does odd-jobs	0.6314	0.0159	-18.3000	0.0000	***
On sick leave	0.1033	0.0219	-10.6900	0.0000	***
Retired/Pensioner	0.0714	0.0051	-36.7200	0.0000	***
Unemployed	0.2201	0.0084	-39.4600	0.0000	***
Never worked	0.0710	0.0240	-7.8400	0.0000	***
Housewife	0.2764	0.0132	-26.9700	0.0000	***
Student	0.5234	0.0082	-41.2900	0.0000	***
Live in a high social vulnerability region (reference "No")					
Yes	0.9444	0.0152	-3.5500	0.0000	***
Level of Education (reference "Higher Education Complete")					
Non-Literate/Incomplete Primary	0.8319	0.0234	-6.5300	0.0000	***
Elementary I Complete/Incomplete Elementary II	0.8693	0.0196	-6.2100	0.0000	***
Elementary II Completo/High School Incompleto	0.8825	0.0172	-6.4300	0.0000	***
High School Complete / Higher Education Incomplete	0.9326	0.0106	-6.1600	0.0000	***
Populational Density	1.0016	0.0004	4.2700	0.0000	***
Family status (reference "Responsible person")					
Spouse / Partner	0.9294	0.0117	-5.8000	0.0000	***
Child / Stepchild	0.7510	0.0102	-21.1800	0.0000	***
Other Relative	0.7498	0.0136	-15.8900	0.0000	***
Other Resident	0.7608	0.0227	-9.1400	0.0000	***

Resident Employee	0.0742	0.0196	-9.8600	0.0000	***
Relative of Resident Employee	0.5747	0.1948	-1.6300	0.1020	
Constant	0.6739	0.0369	-7.2100	0.0000	***

Note: (.) p <0.1; (*) p <0.5; (**) p <0.01; (***) p <0.001

Table B.3: Mandatory/Fixed activities model before the introduction of instrumental variable

Discretionary/Flexible activities model before the introduction of the instrumental variable (n = 47167)					
Model summary					
		R^2 McFadden		0.0665	
		AIC		44724.61	
		Log pseudolikelihood		-22327.303	
Independent Variable	**IRR**	**Robust Std. Error**	**Z**	**P-value**	
Accesibility (90 minutes)	1.384	0.100	4.480	0.000	**
Family per capita income (in thousand reais)	1.147	0.021	7.630	0.000	***
(Family per capita income (in thousand reais)) ^ 2	0.994	0.001	-4.720	0.000	***
Age	1.018	0.004	4.450	0.000	***
(Age) ^ 2	1.000	0.000	-5.330	0.000	***
Family per capita private vehicle	1.136	0.038	3.790	0.000	***
Gender (reference "Male")					
Female	0.955	0.023	-1.920	0.055	.
Number of people in the family	0.957	0.011	-4.020	0.000	***
Proportion of self-declared black population in the region	0.673	0.074	-3.600	0.000	***
Study Status (reference "No")					
Primary/Elementary	0.800	0.143	-1.250	0.211	
Secondary/Middle	0.926	0.125	-0.560	0.572	
Higher/University	0.879	0.056	-2.050	0.041	*
Other	1.087	0.108	0.840	0.401	
Employment status (reference "Has a regular job")					
Does odd-jobs	0.988	0.061	-0.200	0.841	
On sick leave	0.722	0.123	-1.910	0.056	.
Retired/Pensioner	1.506	0.056	11.020	0.000	***
Unemployed	1.343	0.086	4.610	0.000	***
Never worked	0.936	0.265	-0.240	0.814	
Housewife	1.657	0.108	7.720	0.000	***
Student	0.872	0.094	-1.270	0.204	
Live in a high social vulnerability region (reference "No")					
Yes	0.761	0.047	-4.420	0.000	***
Level of Education (reference "Higher Education Complete")					
Non-Literate/Incomplete Primary	0.568	0.038	-8.430	0.000	***
Elementary I Complete/Incomplete Elementary II	0.643	0.036	-7.890	0.000	***
Elementary II Complete/High School Incomplete	0.629	0.033	-8.840	0.000	***
High School Complete / Higher Education Incomplete	0.714	0.023	-10.660	0.000	***
Individual income (reference "Did not answer")					
Yes	1.248	0.030	9.260	0.000	***
No	0.912	0.056	-1.510	0.132	
Populational Density	1.002	0.001	2.090	0.036	*
Family status (reference "Responsible person")					
Spouse / Partner	0.811	0.025	-6.900	0.000	***
Child / Stepchild	0.784	0.033	-5.780	0.000	***
Other Relative	0.594	0.034	-9.090	0.000	***
Other Resident	1.035	0.102	0.350	0.725	
Resident Employee	0.965	0.148	-0.230	0.814	
Relative of Resident Employee	0.000	0.000	-26.260	0.000	***
Constant	0.115	0.015	-16.150	0.000	***

Note: (.) p <0.1; (*) p <0.5; (**) p <0.01; (***) p <0.001