Accessibility in São Paulo: an individual road to equity?

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Abstract

Unequal access to urban opportunities is a challenge for planners and policy makers, particularly in cities of the Global South. This study investigates inequalities in accessibility in São Paulo from an individual-based perspective, adopting a methodological approach that overcomes the high computational and data requirements that typically hinder large-scale applications of individual-based accessibility metrics. The adoption of individual accessibility metrics that can be aggregated a posteriori by economic class, transport mode use, and spatially, produced increased understanding of accessibility patterns both across and within population groups. The analysis revealed that individuals from the upper classes have access to significantly more opportunities than their lower-class counterparts. Results across modes of transport showed that inequalities related to transport modes reinforce and aggravate inequalities originated from distinct location patterns. The study produced evidence that the use of cars and motorbikes enable individuals to improve their own accessibility levels with a positive effect on equity levels across economic classes. The effects of such individual initiatives on equity are, however, unsustainable in the longer run, highlighting the need for public policies that address the roots of access inequality in São Paulo: an inequitable public transport system and strong disparity in locational advantages across economic classes.

KEYWORDS: Individual Accessibility, Transport modes, Inequality, São Paulo.

1 Introduction

Accessibility can be understood as the ease with which people can access urban activities and opportunities using the transportation infrastructure available (Geurs & van Wee, 2004). Those opportunities, however, are not evenly accessible to all individuals or social groups and dealing with such inequalities is one of the major challenges faced by cities around the world. Inequalities in accessibility can be explored via two perspectives: the place-based perspective, which is useful to reveal inequalities among socio-economic groups stemming from their spatial location (Giannotti et al., 2021; Neutens, Schwanen, et al., 2010; Pereira et al., 2019); and the individual-based perspective, which allows for the understanding of inequalities stemming from individual capabilities, preferences, and constraints affecting their access to opportunities (Kwan, 1998, 1999; Neutens, Schwanen, et al., 2010).

Although accessibility has been traditionally studied from a place-based perspective, it is argued that this does not adequately represent the complexity of the accessibility concept (Handy & Niemeier, 1997; Kwan, 2013; Miller, 2007). This approach assumes all individuals living in the same place have the same levels of accessibility, which is not an accurate portrait of reality. Differences in individual accessibilities may stem from factors such as access to different means of transport, personal responsibilities which impact an individual's time constraints, as well as personal preferences and necessities. Individual-based accessibility studies allow for individual factors to be considered into the accessibility measurement.

There is evidence that individual based-accessibility metrics (IBAMs) are better suited for studies of inequalities in accessibility than place-based accessibility metrics, as they are capable of capturing individual-level differences that are masked by place-based aggregates (PBAMs) (Kwan, 1998; Neutens, Schwanen, et al., 2010). Yet, there are relatively few empirical studies which adopt individual-based accessibility to look specifically at inequalities, as well as a clear predominance of place-based studies over individual-based in the overall literature on accessibility.

A wider adoption of individual-based studies for empirical applications has been hindered by the availability of data on individuals' activities and schedules, as well as the difficulty of scaling individual-based methods to large populations (Geurs & van Wee, 2004; Neutens et al., 2011). Hence, IBAMs are usually applied to small population samples and/or geographic areas (Casas, 2007; Kamruzzaman & Hine, 2012; Kim & Kwan, 2003; Kwan, 1999; Weber & Kwan, 2002). Other methodological challenges that constrain a wider adoption of IBAMs are the difficulties with the spatial representation of results (Charleux, 2015; Delafontaine et al., 2012), and their meaningful reaggregation (Horner and Dawn 2014) - both geographically and into population groups.

This paper faces these methodological challenges to employ an individual-based approach to the study of inequality in accessibility in São Paulo, the largest city in Brazil. This study builds on a body of research that looks at inequality in transport in São Paulo (Bittencourt & Giannotti, 2021; Boisjoly et al., 2017; Moreno-Monroy et al., 2018; Slovic et al., 2019) as well as other Brazilian cities (Bittencourt et al., 2021; Boisjoly et al., 2020; Pereira, 2019; Pereira et al., 2019) from the placed-based perspective. To the best of our knowledge, there are no published studies of individual-based accessibility applied to Brazilian or other Latin American cities. By investigating accessibility inequality in São Paulo from a individual-based perspective, this paper aims to unveil aspects of São Paulo's inequality that could not be detected by previous studies due to their focus on places rather than on individuals.

This paper's contributions are twofold. First, it contributes to the understanding of inequalities in accessibility in São Paulo, by studying them from an individual-based perspective. Second, it contributes to the wider adoption of IBAMs to large-scale empirical studies by proposing strategies to deal with the challenges of scaling an individual-based study of accessibility to a large study area.

This paper is organised as follows. Section 2 presents an overview of accessibility inequalities studies, with a focus on São Paulo. Section 3 discusses IBAMs and the challenges hindering their wider adoption for large-scale empirical studies. Section 4 introduces the methodology adopted, including the strategies employed to scale the study to a large and populous city. Section 5 presents an overview of São Paulo and its transport trends. Section 6 presents and discusses the results of the individual based accessibility analysis across economic classes and transport modes. The article concludes with a discussion on the main findings in the context of known transport trends and public policy matters in São Paulo.

2 Unequal Accessibilities: from place to people

The study of inequalities in transport is a relatively recent but growing trend, which stems from an increasing recognition of the importance of assessing equity implications of transport systems, policies, and investments. Such studies look at how the combined effects of land use spatial distribution and transport systems enable different levels of access to opportunities to different factions of society. Based on the idea that transport contributes to 'space-time convergence' by reducing travel times and bringing 'places closer together' (Miller, 2007, p. 505), studies have looked into the role of transport in reducing or reinforcing existing inequalities as well as how inequalities in accessibility are related to other dimensions of inequality, such as deprivation and lack of basic services.

Brazilian cities are well-known for their socio-economic inequalities, which are mirrored by transport accessibility (Bittencourt et al., 2021; Boisjoly et al., 2020; Pereira, 2019; Pereira et al., 2019). São Paulo, as Brazil's largest and richest city, has been subject to various recent studies concerning inequalities in transport. In a study evaluating accessibility to jobs, education, and healthcare opportunities on the 20 largest Brazilian cities, São Paulo was found to be the most unequal (Pereira et al., 2019). Comparative studies with London and New York showed similar results

(Bittencourt & Giannotti, 2021; Giannotti et al., 2021). The relationship between low accessibility and other dimensions of inequality as well as social issues in São Paulo have also been investigated. Moreno-Monroy et al. (2018) and Pizzol et al (2021) found evidence that students from upper income areas have significant advantages in access to schools. Boisjoly et al. (2017) linked low accessibility to high informality rates among low wage workers, and Slovic et al (2019) found evidence that low accessibility areas have worse provision of public services such as water supply, sewage, and garbage collection.

Place-based studies of inequality in accessibility have made significant advances in disaggregating PBAMs by assuming groups present different capabilities and transport-related constraints as well as distinct spatial distributions. Some studies also assume distinct groups access different urban opportunities, such as types of jobs (Giannotti et al., 2021) or schools (Pizzol et al., 2021). As accessibility levels are attached to spatial units and strongly shaped by the spatial distribution of opportunities and transport systems, traditional mapping methods such as choropleth classification can be ineffective in revealing differences in accessibility levels for distinct population groups. Thus, place-based studies tend to represent inequalities by using statistics, inequality indices - i.e. Palma ratio (Pereira et al., 2019; Pritchard et al., 2019) or Gini index (Giannotti et al., 2021) - or alternative cartographical methods (Bittencourt & Giannotti, 2021).

Conversely, individual-based approaches, such as the one proposed here, enable accessibility studies to unfold aggregated results and study intra-group and intra-location heterogeneities, providing a more in-depth understanding of inequalities of accessibility.

3 Individual-based accessibility metrics

IBAMs stem from Hägerstrand's (1970) time geography theoretical and methodological framework, which allow for individual space and time constraints to be incorporated into the measurement of accessibility (Kwan, 1998; Miller, 1999; Neutens, Schwanen, et al., 2010; Patterson & Farber, 2015). Accessibility is operationalised from the main concepts of space-time path, defined as the trajectory of an individual (or any material object) in time and space, and space-time prism, which represents the space of possible trajectories an individual can take off their main path. The projection of space-time prism in two-dimensional space (the potential-path area - PPA), represents the geographical extent an individual can access. Thus, path and prism define the places an individual can visit considering their space-time constraints.

Different types of IBAMs based on those concepts can be found in the literature. The volume of an individual's space-time prism (Burns, 1979; Miller, 1991) or the area of their PPA (Kamruzzaman & Hine, 2012; Newsome et al., 1998) can be considered as direct proxies for that individual's accessibility. Cumulative opportunities-like metrics can be derived from the number of feasible opportunities in the individual's PPA or prism, stemming from Lenntorp's (1976) work. These metrics can be weighted by their size, distance, or time available to spend on them (Kwan, 1998; Neutens, Schwanen, et al., 2010). Finally, utility-based or logsum metrics (Burns, 1979; Masuyama, 2020; Miller, 1999) are based on a logit model framework and aim to differentiate opportunities by the utility (or benefits) that an individual can obtain by participating on them.

Due to their ability to incorporate individual capabilities, preferences, and constraints, IBAMs are considered to be more theoretically complete than their place-based counterparts (Geurs & van Wee, 2004). The body of literature on IBAMs shows a clear collective effort towards the fulfilment of the method's potential for theoretical completeness (Horner & Downs, 2014; Kwan & Hong, 1998; Lee & Miller, 2019, 2020; Masuyama, 2020; Miller, 1991, 1999; Neutens et al., 2008; Wu et al., 2021). However, such novel methodological approaches are usually demonstrated with empirical analyses on small areas and/or populations. There are few academic articles which focus on the empirical application of IBAMs (see Kwan, 1999), in particular on large urban areas (Widener et al., 2013, 2015). Similarly, IBAMs are yet to be widely adopted by policy-makers and practitioners (Charleux, 2015).

This can be attributed to three main factors: a) the data hungry nature of IBAMs, that require temporally and geographically detailed individual data on schedules and travel diaries; b) the complexity and computational demand of calculating the metrics at individual level; and c) difficulties in presenting and interpreting individual results in a meaningful way, which is relevant for policymaking and practitioners. These factors are discussed below and further addressed in section 4.2, where the methodological strategies adopted to deal with each challenge are detailed.

There is wide recognition of the difficulties caused by IBAMs detailed data requirements (Charleux, 2015; Delafontaine et al., 2012; Neutens et al., 2011). The need for individual activity schedules as input greatly restricts the applicability of IBAMs, since these datasets are rare and, when available, only concern samples of the population. Delafontaine et al (2012) highlight the issue of the representativity of samples and argue this issue puts the usefulness of IBAMs results in question.

The calculation of IBAMs is more complex and demands a higher computational processing power in comparison to PBAMs, mainly due to the computational implementation of space-time constraints. This hindered the further development of IBAMs until the early 1990's, when advances in GIS reignited interest in these metrics (Miller, 1991). Since then, the methodology has greatly advanced, including solutions to lower data requirements and improve scalability (Farber et al., 2013; Neutens et al., 2008; Widener et al., 2013).

Another known challenge for IBAMs is their cartographic representation, which disadvantage such metrics in comparison to PBAMs due to the importance of maps to practitioners and decision makers (Charleux, 2015; Delafontaine et al., 2012). This shortcoming stems from the very nature of IBAMs, which concern individuals rather than places, causing difficulties to attribute accessibility values that belong to moving individuals to a static location[1].

The difficulties with IBAMs' cartographic representation are better understood as part of a wider challenge concerning the aggregation of individual results (Delafontaine et al., 2012; Geurs & van Wee, 2004; Horner & Downs, 2014). This includes aggregation of results into places as well as into population groups to allow analysis of trends across individuals. Drawing conclusions on populations or places based on individual information requires caution, as the generalisation from individual to aggregate may lead to the exception fallacy – the reverse of the ecological fallacy (O'Dowd, 2003). While the ecological fallacy is a well-known problem that occurs when inferring individual information from places, the reverse issue is less common in geography, but particularly relevant for individual-based studies. Hence, drawing conclusions on groups, populations, or places based on individual information remains an obstacle to the wider adoption of IBAMs to empirical studies.

Efforts to tackle these three challenges involved compromises between place-based and individual-based approaches (Farber et al., 2013, 2015; Horner & Downs, 2014; Widener et al., 2013, 2015). One of such efforts is Farber et al.'s (2013) Social Interaction Potential (SIP) metric built upon the concept of joint-accessibility (Neutens et al., 2008), which consists on a measure of the time that two individuals can be co-present in the same location. SIP can be calculated using general OD data instead of individual travel

[1] For a review of IBAMs mapping efforts, see Delafontaine, Neutens, and Van de Weghe 2012.

diaries by assigning simplified time budgets to individuals instead of real activity schedules – a strategy that increases scalability at the cost of heterogeneity. Widener and colleagues (2013, 2015) adapted SIP to measure accessibility to supermarkets in large urban regions. Their metric, like SIP, produces results at the group or geographical area levels (albeit derived from individual based concepts) that are meaningful for both cross population and location-based analysis purposes.

4 *Methodology*

This study calculated two versions of IBAMs: a) a cumulative opportunities-like metric, which accounts for the number of opportunities individuals can reach in their time budget – here referred to as 'cardinal'[2] accessibility; and b) a 'geometric' accessibility, which is based on the size of an individual's reachable geographical area (PPA). Both metrics can be interpreted as measures of freedom of choice (Neutens, Versichele, et al., 2010), since an individual is more likely to find suitable locations to carry out desired activities within larger opportunity sets and geographical areas. The cardinal accessibility considers the spatial distribution of opportunities within the study area, while the geometric accessibility is only affected by the individual's mobility and time budget.

Both geometric and cardinal metrics are based on the space-time feasibility concept (Kwan, 1998). The diagram in Figure 1a depicts a hypothetical individual's home and work locations (H and W in the map, respectively), as well as their commuting trajectory and a set of discretionary activity locations (represented as blue points; activity points A1, A2, and A3 highlighted for illustrative purposes). Each individual has a time budget, defined as the amount of time remaining after the main activities at work and home are completed, which will be used to select the opportunities the individual can participate.

[2] Name derived from the 'cardinality' of the individual's FOS.

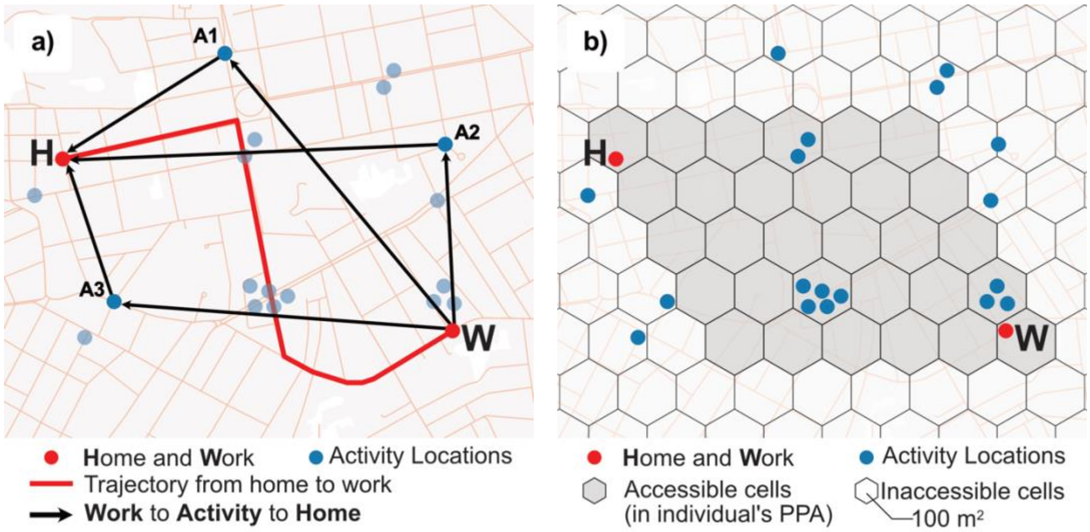

Figure 1 – A hypothetical individual's feasible opportunity set represented as discrete activity locations and as cells of a hexagonal grid.

The accessibility a_i^k of individual i to activity k is given by equation (1):

$$a_i^k = \begin{cases} 1, & if\ (t_{wk} + t_{kh} + t_k) \leq tb_i \\ 0, & otherwise \end{cases} \tag{1}$$

Where:

- t_{wk} is the travel time from work to activity location k;
- t_{kh} is the travel time from the activity location k to home;
- t_k is the minimum time required to carry out activity k;
- tb_i is the time budget of individual i.

Thus, activities are considered feasible if the sum of the time required to a) reach the activity from previous location, b) complete the activity, and c) to travel from the activity location to the next destination fits within the individual's time budget. The overall accessibility A_i of individual i can then be calculated according to equation (2):

$$A_i = \sum_{k \in K} a_i^k \tag{2}$$

Where:

- K is the set of all opportunities in the study area.

The difference between cardinal and geometric metrics relies on the nature of the K set: when K contains geographic locations (such as grid cells), the resulting metric will be geometric; when K contains discrete activity locations, the resulting metric will be cardinal.

In the example in Figure 1b, the individual's geometric accessibility is 3000 m^2 (30 cells of 100 m^2 each in the PPA, in grey), representing the geographical area the individual can reach within their time budget and considering their time constraints. This same individual's cardinal accessibility is 10, representing the number of activity locations inside the individual's PPA. This example illustrates the distinction between the two metrics: while this individual can reach a large geographical area (as measured by the geometric accessibility), the activities they can access are few and concentrated in clusters within that area (as measured by the cardinal accessibility).

The cardinal metric corresponds to the cumulative opportunities-like metrics used by Kwan (1998) and Neutens et al. (2010), while the geometric one is similar to metrics based on the size of the accessible road network (Kwan 1998, Miller 2007), adapted for grid cells.

4.1 Datasets

This study used data from the São Paulo Origin and Destination (OD) 2017 survey[3], which contains information on 38 million individual trips of all purposes in the São Paulo Metropolitan Region (Metrô, 2019). Each trip contains information on the geographic coordinates of the origin and destination points, purpose, demographic information on the traveller, mode of transport, and an expansion factor. The latter is a statistical value that indicates each surveyed trip's representativity on the overall population. All commuting to work trips that begin and end within the São Paulo municipality were selected for this study, totalling approximately 4.5 million trips.

The economic class of individuals was used as a proxy to socio-economic classes. The OD Survey classifies individuals into five economic classes (A, B2, B2, C1, C2, and D - E) according to the Brazil Economic Classification Criterion[4], which is calculated based on individuals' purchasing power. The upper class (A) was further disaggregated into classes A1 (the 20% higher income individuals in class A) and A2 to better portray the representativity of those groups and their distinct spatial distributions[5].

[3] http://www.metro.sp.gov.br/pesquisa-od/
[4] Translated from 'Critério de Classificação Econômica Brasil', in Portuguese.
[5] The spatial distribution of classes A1 and A2 can be observed in the maps in Figure 3.

The spatial distribution of opportunities in the study area was obtained from the CNEFE dataset (National Cadastre of Addresses for Statistical Purposes[6]), which is part of the 2010 Brazilian Census (IBGE, 2012). Opportunities were grouped into three categories: a) healthcare; b) education; and c) commercial and services. Opportunities were not differentiated in terms of size, opening hours, or any other characteristic.

Spatial information on road network and urbanised areas was extracted from OpenStreetMap[7] (OSM). The OSM road network was augmented with SRTM (Shuttle Radar Topography Mission) elevation data (Farr et al., 2007), as steep slopes can significantly impact walking and cycling travel times. To calculate driving speeds accurately, average speeds per street segment were obtained from Uber Movement[8]. Motorcycles were assumed to travel at the maximum speed allowed on each street segment, thus disregarding congestion conditions, in line with OD data which indicates that, on average, trips by motorcycle are 60% faster than trips by car. Public transport travel times were calculated using data in General Transit Feed Specification (GTFS) format, freely available for the study area and provided by the public transport agencies in São Paulo (SPTrans[9] and EMTU[10]).

4.2 Implementation strategy

In order to apply IBAMs for the entire area and population of São Paulo, the study adopted a set of strategies, detailed below.

4.2.1 Adoption of a 'single activity after work' scenario

A 'single activity after work' scenario was adopted following Farber et al (2013) and Widener et al. (2013, 2015), in order to avoid the need for detailed individual activity diaries and reduce computational burden.

A time budget of 90 minutes was used for all individuals, regardless of economic class. The minimum time for participating in an activity was set to 15 minutes, which represents quick everyday errands. Although this represents a simplification with possible effect on diminishing heterogeneity, and hence inequalities, in the results, this compromise does not introduce significant bias to the results since they affect all people in the study area equally.

[6] Translated from 'Cadastro Nacional de Endereços para Fins Estatísticos', in Portuguese.
[7] Available at https://www.openstreetmap.org/
[8] Uber Movement, (c) 2019 Uber Technologies, Inc., *https://movement.uber.com*
[9] SPtrans - São Paulo Transporte S/A, available at *http://www.sptrans.com.br/desenvolvedores/login-desenvolvedores/*
[10] EMTU - Empresa Metropolitana de Transportes Urbanos de São Paulo, available at https://www.emtu.sp.gov.br/dadosAbertosEmtu/

Travel times by public transport were calculated considering a 5pm to 7pm departure time window[11], with departures at every minute. The public transport travel-time matrix was built using the median travel time over that window, to account for variations in public transport service availability. Travel times by car were calculated using a single departure time, considering congestion levels at 6pm. Travel by walking, bicycle, and motorcycle are considered not to be affected by congestion.

4.2.2 Hexagonal spatial representation

Opportunities and residential locations were allocated to cells of a hexagonal grid based on their geographic coordinates (see Figure 2). This allowed for travel-time matrices to be calculated for all transport modes for each pair of hexagons in the study area instead for each pair of locations. Those times were used as proxies for actual travel times between activity locations situated inside those hexagons, resulting in a small loss of precision in travel times for home and activity locations that are farther away from the cells' centroids.

The grid was built using Uber's H3 indexing system[12], at resolution 9 (approximately 357m diagonal). Travel times were calculated using the R statistical programming language (R. Core Team, 2016) using packages dodgr (Padgham, 2019) for walking, cycling, driving and motorcycle travel times, and r5r (Pereira, Saraiva, et al., 2021) for public transportation travel times.

4.2.3 *A posteriori* aggregation

Unlike the metrics proposed by Farber et al (2013) and Widener et al (2013, 2015), the metrics computed here are not aggregate from the outset. Instead, accessibility is computed for each individual and results aggregated *a posteriori*, based on individual information available in the OD Survey dataset. This strategy adds flexibility to the analysis, since individuals can be categorised in groups as well as aggregated into sub-categories and different social dimensions as needed.

A similar principle was adopted for the cartographic representation of results, taking advantage of the flexibility of *a posteriori* aggregation in geographical areas as well as population groups. Hence, different mapping solutions are adopted throughout the results section to illustrate the relevant nuances of the results.

[11] Based on OD Survey data, most individuals across all economic classes return home within those times.
[12] H3 Geospatial Indexing System, Uber Technologies, Inc., *https://h3geo.org/*

5 Study Area

São Paulo has 11.2 million inhabitants (IBGE, 2012) and is the largest city in Brazil, as well as its main economic and financial centre. The study is limited to the municipality's limits (Figure 2) due to the lack of public transport information in GTFS format for the entire metropolitan region.

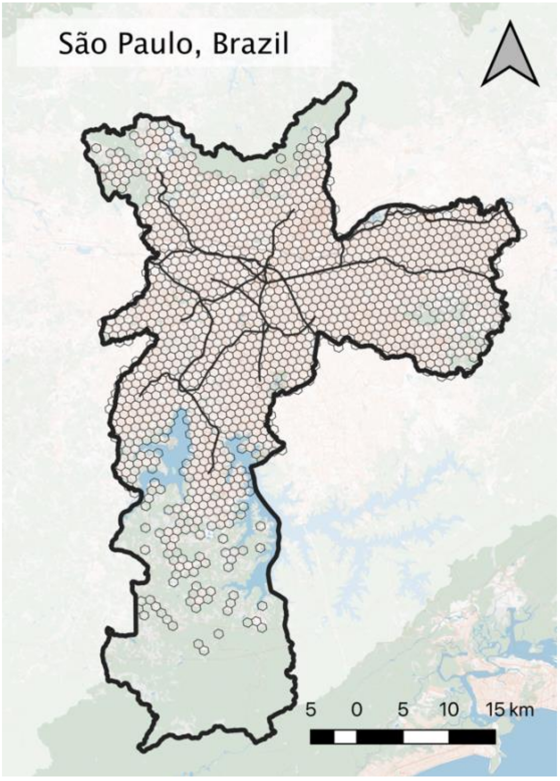

Figure 2 – The municipality of São Paulo and its main geographical features, metro, and rail networks, and regular hexagonal grid of the urban area.

The composition of the working population in the study area by economic class is presented in Table 1, which shows that only a small percentage of the working population of São Paulo (10.5%) belongs to the upper classes (A1 and A2), while the remaining 89.5% of people are divided between classes B, C, D and E.

Table 1 - Proportion of individuals by economic class in São Paulo.

Data source: São Paulo OD Survey, 2017.

Population		Transport Modes					
Group	%	Walking	Bicycle	Motorcycle	Car	Bus	Transit[13]
A1	1.2%	8.8%	2.1%	3.0%	77.8%	3.2%	5.1%
A2	9.3%	12.1%	2.0%	3.5%	65.8%	8.7%	7.8%
B1	12.4%	14.0%	1.4%	4.8%	54.6%	12.8%	12.3%
B2	32.2%	19.9%	1.4%	5.6%	41.7%	21.1%	10.4%
C1	25.8%	29.2%	1.9%	5.7%	24.8%	30.8%	7.6%
C2	15.5%	40.3%	1.9%	3.5%	12.4%	36.4%	5.4%
D - E	3.5%	44.8%	6.8%	3.5%	6.6%	33.3%	5.0%
All	100%	24.7%	1.8%	4.9%	35.8%	24.0%	8.6%

Table 1also shows that private cars are the predominant mode of transport to work in the city (35.8%), followed by walking (24.7%) and bus (24%). Only 8.6% of people use the metro system or suburban trains to commute, likely due the limited reach and capacity of São Paulo's rail network.

The modal split for different economic classes can also be observed in Table 1. The associations between upper economic classes (A1, A2, B1 and B2) with the use of cars and between lower economic classes with public transport are clear from the table. However, the data shows the picture is more complex and there is greater heterogeneity in how economic classes use transport modes. Over 8% of A1 class commutes to work by public transport, a percentage that increases across the class hierarchy up to 41.8% for class C2, slightly decreasing to 38.3% for class E-D. Within public transport users, middle-high classes (B1 and B2) present the highest percentage of transit users (10-12%) while buses are most used by lower economic classes C1, C2 and D-E. Walking also increases as economic power decreases: over 40% of people in classes C2, D and E commute by foot, compared to less than 10% of class A1. Bicycle use is relatively stable across classes (between 1.4 and 2.1%), except for class D-E which has 6.8% of individuals cycling to work.

The maps in Figure 3 show the upper classes tend to reside in central areas, while the lower classes live mainly in the peripheral areas of São Paulo. In contrast, there is a concentration of jobs for all economic classes in the central area of São Paulo, albeit the job location of lower classes is more evenly distributed than that of the upper classes. Commerce and services opportunities are spread throughout the city, but with

[13] The mode 'transit' includes all available combinations of public transportation: bus, metro, and suburban trains. It also including walking (up to 800 meters).

a higher concentration in the city centre. Healthcare opportunities also tend to be more centrally located, while schools are more evenly distributed.

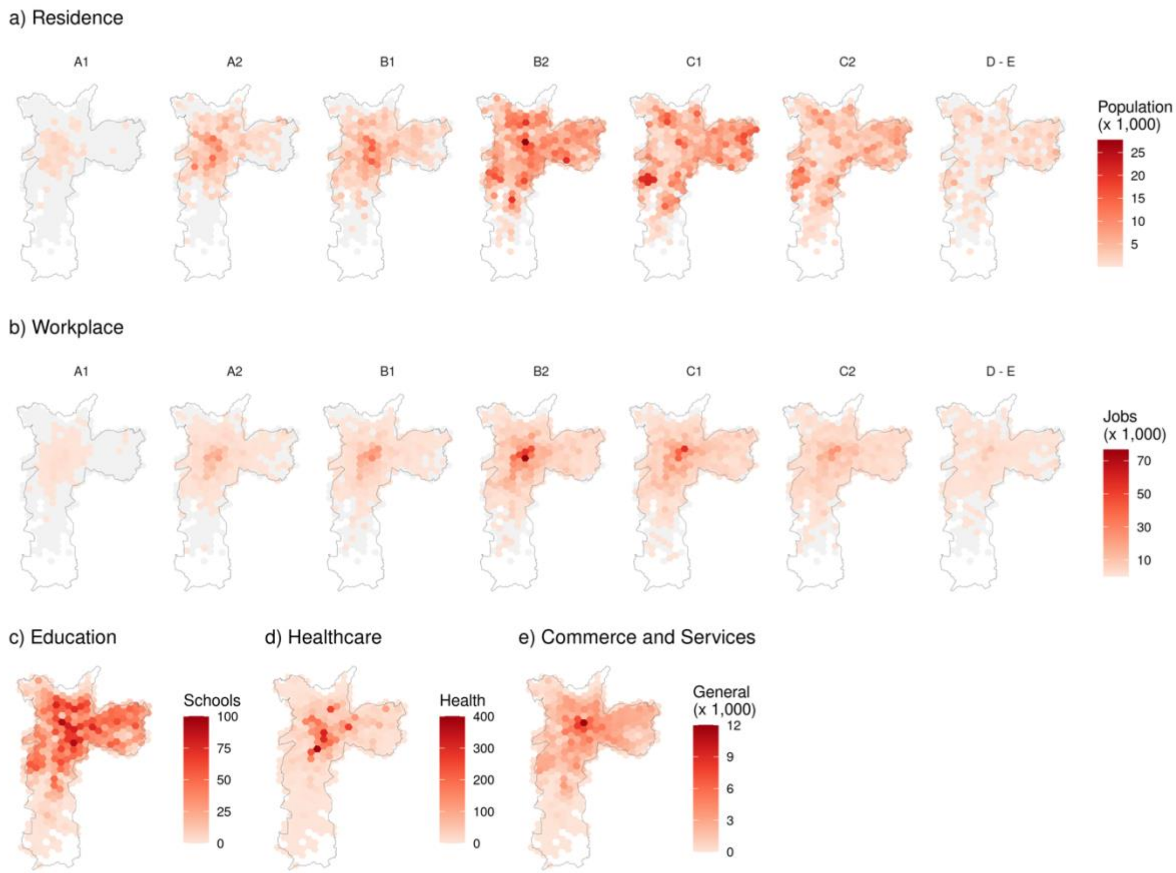

Figure 3 - Residential, workplace, and land use distributions in São Paulo.

6 Individual accessibility in São Paulo

As the results of the individual analysis using geometric and cardinal accessibility metrics were broadly similar, the first part of this section will focus on the cardinal accessibility results. The second part of this section will look into the exception to this rule, where results for the two metrics were divergent and their comparison provided further insights into the inequalities in accessibility levels in São Paulo.

6.1 Cardinal Accessibility Results

The analysis of cardinal accessibility was carried out separately for three categories of opportunities: commercial and services, healthcare, and education. Figure 4a shows cardinal results calculated using individual's transport mode information from the OD Survey and Figure 4b shows results computed assuming an artificial scenario where all individuals use a single transport mode (private motorized transport, no congestion).

Figure 4a shows how relative accessibility varies across economic classes, with each class presenting more individuals with accessibility above average than the class immediately below it. The two top economic classes (A1 and A2) present more than 50% of individuals with accessibility above average, while class B1 is evenly divided. At the other end of the spectrum, over 93% of individuals from bottom classes (D – E) present accessibility below average, highlighting the deep inequalities in the study area.

The results for the artificial scenario results (Figure 4b) shows a clear improvement in accessibility across classes, in particular to lower economic classes, which demonstrates differences in transport modes exacerbate inequalities between economic classes. This scenario also confirms the role of land use distribution to accessibility inequality, where upper classes benefit from the accessibility granted by central locations while lower classes live farther away from opportunities and rely on transport efficacy, corroborating findings by Slovic et al (2019).

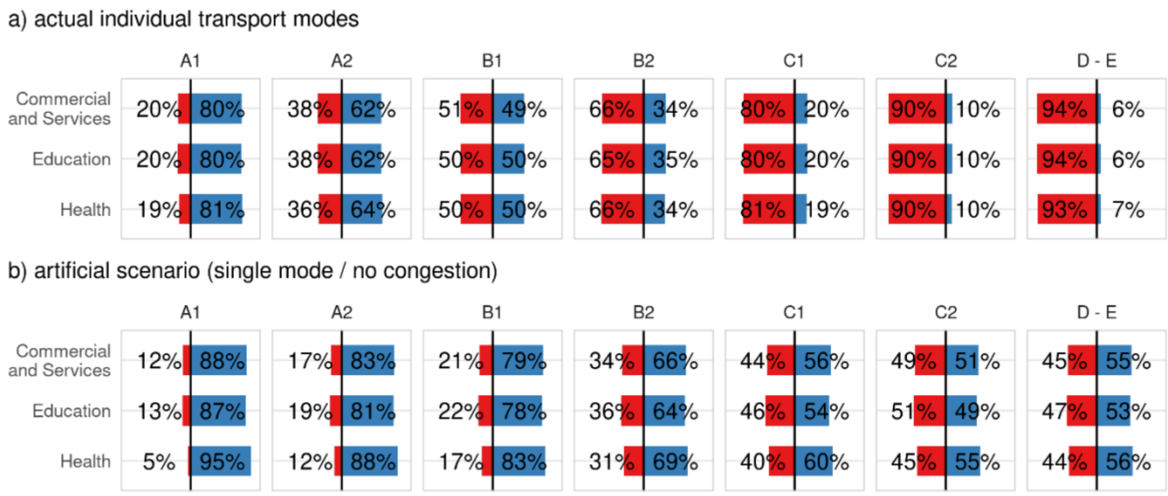

Figure 4 - Percentage of each group's population with cardinal accessibility levels above and below the overall average.

Figure 4 shows that results are largely similar for all economic classes across the different categories of opportunities analysed. This indicates that accessibility to commerce and services can be used to represent access to key services such as health and education and, thus, is suitable to measure overall inequality in access in São Paulo. The remaining analyses will focus on this category.

The cardinal accessibility results for commercial and services shown in Figure 4 were further detailed in Figure 5a, which allows the analysis *within* as well as *across* population groups. The graphs show the median, lower and upper quartile, as well as the 5th and 95th percentiles of accessibility for each class, thus unfolding individual accessibility levels within each economic class and revealing heterogeneity.

Looking across upper quartile values, it is clear there is a sharp division among São Paulo's working population, as upper economic classes (A1 to B2) present significantly higher accessibility levels than lower economic classes (C1 to D – E). To illustrate, individuals on the accessibility upper quartile of class B2 can access 10 times more opportunities than their counterparts on class C1 in the same 90 minutes time budget. The gap reaches 39 times between economic classes A1 and D – E. Conversely, the gap between the accessibility lower quartiles of all classes, apart from A1, is much smaller. In short, individuals with very high accessibility levels belong almost exclusively to the upper economic classes, while individuals with low accessibility are present across all economic classes.

It is worth noting the lower quartile of accessibility of groups B2 to D – E is zero, which indicates that a time budget of 90 minutes is not sufficient for more than 25% of those individuals to carry out extra activities after work – unlike those in upper classes. Also, the accessibility ranges of upper economic classes (A and B) are much larger than those of the lower classes (C and D-E), a result of combined effects of residential location and transport mode choice. Upper classes tend to be more centrally located and are higher users of private transport modes, while lower economic classes tend to live farther from the centre and rely more on public transport (see Figure 3 and Table 1).

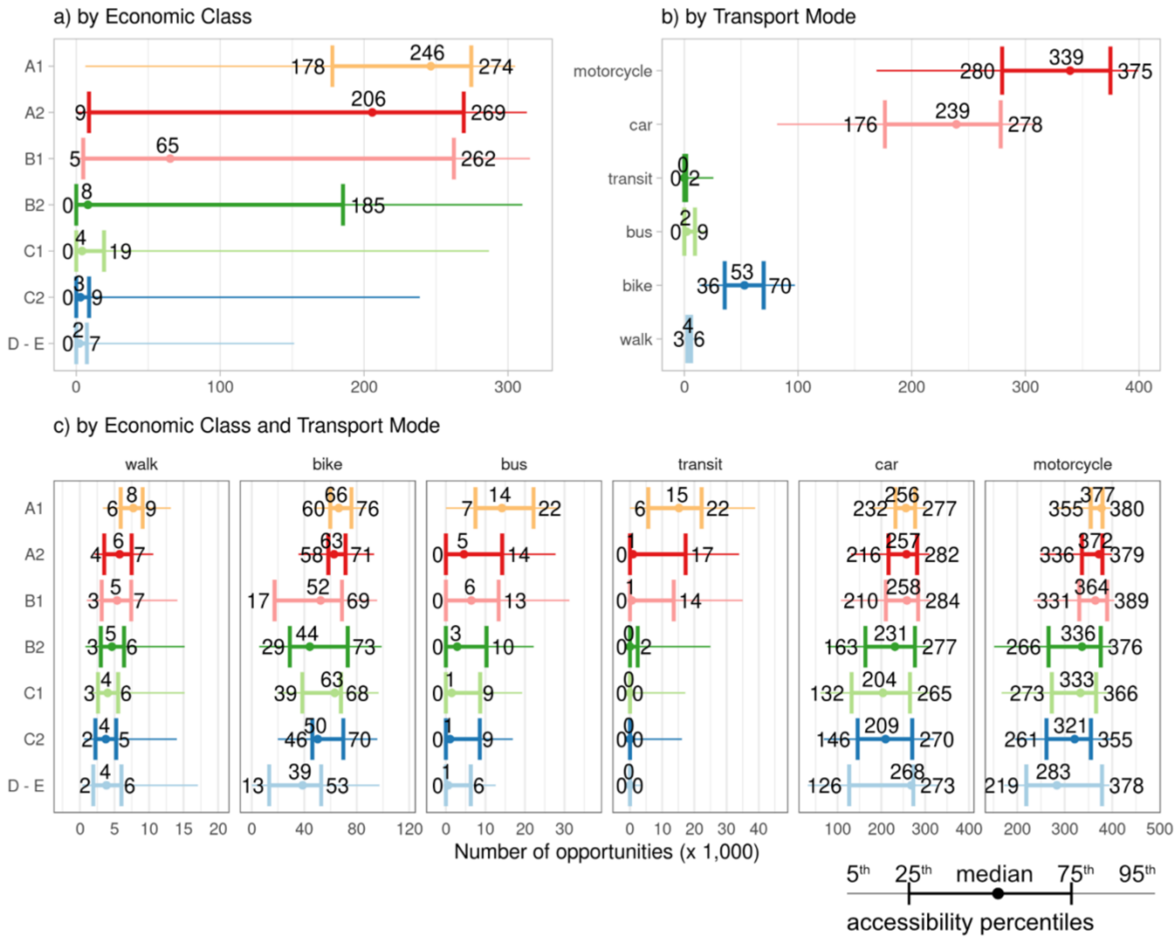

Figure 5 - Distribution of cardinal accessibility.

Figure 5b shows the graphs produced by aggregating results by transport mode users. In comparison to Figure 5a, it is noticeable that the ranges of accessibility within economic class groups is much larger than those by transport mode users. Figure 5b also shows that accessibility of car and motorcycle users, both private and motorized transport modes, are by far the highest in the study area. Motorcycle users' accessibility is higher than that of car users, suggesting the use of motorcycles provides significant accessibility gains, which benefits individuals in middle economic classes (B2 and C1), who most use this travel mode (5.6% and 5.7%, respectively).

The median accessibility values of bus and transit users are the lowest in the study area, indicating that users of São Paulo's public transportation system do not benefit from easy access to discretionary activities after work. The fact that 42% of bus users and 69% of transit users have accessibility equal to zero means that the allocated 90 minutes time budget considered in this scenario is entirely consumed by their commute home, indicating long journeys for those users. Although a small proportion of individuals commute by bicycle, they have significantly higher accessibility than bus and transit users - a consequence of short distances typically travelled by bicycle users.

Figure 5c, which shows accessibility by economic class and mode of transport combined, confirms the pattern of inequality in accessibility levels by economic classes is maintained regardless of transport mode but it is more pronounced among users of public transportation (bus and transit). Analysis across users of the same transport mode reveals that upper classes' individuals consistently present higher accessibility than individuals in lower classes. This can be attributed to an effect of the more advantageous residential locations of the upper classes which allows them to make decisions on transport mode based on convenience. In the case of transit, central residential locations might contribute to easy access to metro stations, thus avoiding longer trips and transfers between transport modes. Similarly, Figure 5c reveals that private transportation users (car or motorcycle) from the lower classes have significantly higher accessibility levels than individuals of the same class who use public transport.

The maps in Figure 6a show the residential locations of individuals with accessibility below the lower quartile for each economic class. The darker hexagons, indicating a higher number of individuals in this category at that location, tend to form a ring around the city centre and along the edges of the urbanised area. Most individuals with low accessibility belong to economic classes B2 to C2, which are also the most populous classes in the study area (32% and 26% of the population, respectively), but the fact their presence is not as significant in the maps that portray the residential locations of individuals with accessibility above the upper quartile (Figure 6b) is meaningful. Maps in Figure 6b show that a large proportion of individuals with higher levels of accessibility belongs to groups A2, B1, and B2, a pattern not shaped by A2 and B1's overall representation in the study area's population (9% and 12%, respectively).

Although the maps in Figure 6a only include a quarter of the total working population, they can provide useful insights for policy making, since they indicate the location where accessibility-increasing policies and investments would be more effective in reaching low accessibility population groups. For example, better transportation links between the dark red areas in the eastern, northern, and southern edges of the São Paulo municipality to the city centre would benefit the largest number of individuals with low accessibility in the middle to lower economic classes. Alternatively, policies that create incentives for business to invest and/or relocate to those areas could also be effective in increasing the accessibility of residents without creating extra pressures in the existing transportation system nor requiring costly and time-consuming investments in the public transport infrastructure.

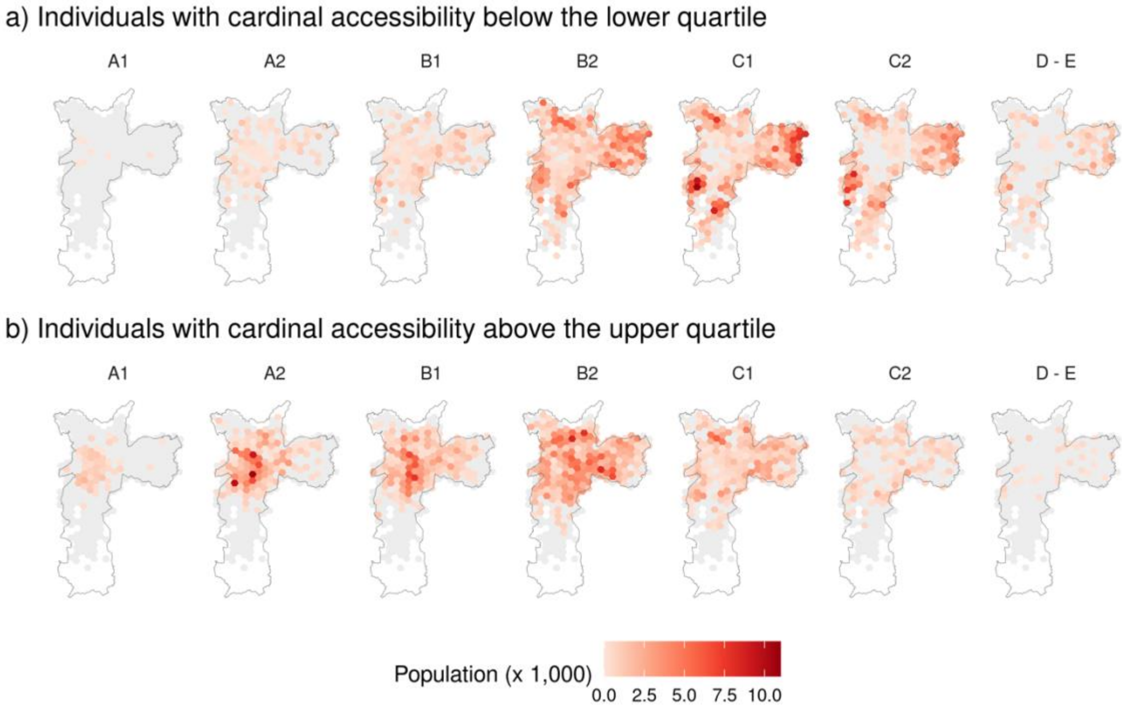

Figure 6 – Individuals with accessibility below the lower quartile (a) and above the upper quartile (b), by economic class. Urbanised area shown in light grey.

6.2 Cardinal versus Geometric Accessibility

Cardinal and geometric accessibility results can be analysed together to further investigate the interaction between mobility and land use distribution. Although their overall results are highly correlated across the entire population, a small percentage of the individuals (6.9%) are exceptions and present contrasting accessibility levels. Those individuals have access to many opportunities in a small geographic area due to advantageous residential and/or workplace location, regardless of their low mobility (high cardinal and low geometric accessibility); or have access to a large geographic area due to their high mobility, but few opportunities are located in that area (low cardinal and high geometric accessibility).

Individuals with high cardinal accessibility and low geometric accessibility are mainly concentrated in central areas and neighbourhoods close to the city centre (see Figure 7a), belong to all economic classes (Figure 7c), and mostly walk to work (Figure 7d). These results are consistent with individuals who can afford to live in areas denser of opportunities, where owning a motor vehicle is deemed unnecessary. A smaller percentage of those individuals commute by transit and live farther away from the city centre but closer to metro and train lines (represented in grey in Figure 7a).

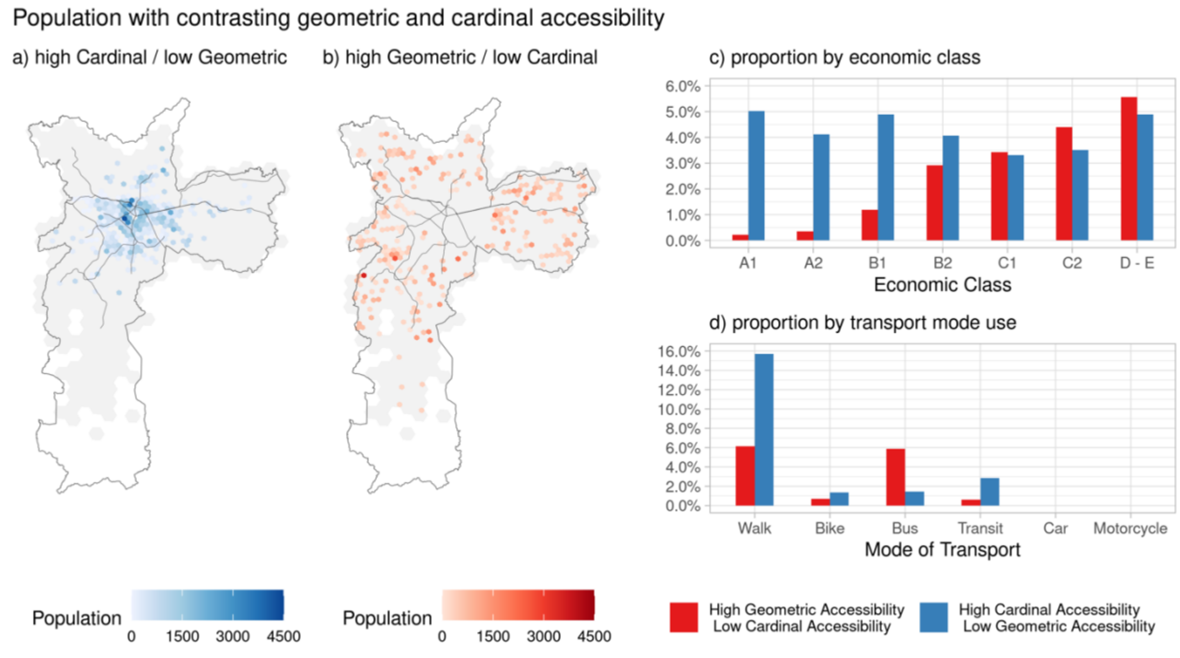

Figure 7 – Comparison between individuals' cardinal and geometric accessibilities.

In contrast, individuals with high geometric accessibility and low cardinal accessibility live mostly in the peripheral areas of São Paulo (Figure 7b), belong almost exclusively to the middle and lower classes (Figure 7c), and commute by bus or on foot (Figure 7d). Notably, none of those individuals use private transportation modes (cars or motorcycles), yet they can reach large geographic areas within the 90 minutes time budget. This can be explained by their short commuting times, which allow them to use a larger portion of their time budgets for discretionary activities. However, those individuals live and work in peripheral areas with few opportunities to reach, so the mobility granted by their extra free time is not enough to grant them extra accessibility.

Although this analysis only provides an insight into exceptional cases and thus cannot be generalised for the entire area or population, it demonstrates that, for the case of São Paulo, improving transport systems without addressing the challenges imposed by land use distribution has limited effects.

7 Discussion and conclusion

IBAMs were used to study inequality in access to opportunities in São Paulo considering individuals' economic classes and travel behaviour. A set of strategies was adopted to counter known issues hindering large-scale application of IBAMs, such as a 'single activity after work' scenario to reduce data requirements and a regular grid to ease travel times computation. While those strategies represent a compromise on the heterogeneity and level of detail typical of IBAMs, they allowed the methodology to be successfully scaled and applied to study accessibility in São Paulo. They also allowed for multiple transport modes to be investigated, using individual's actual travel behaviour information, obtained from OD Survey data. Thus, the effect of the interplay between transport mode, land use distribution, and economic classes onto accessibility levels could be investigated within a single framework and patterns across groups and overall population as well as their heterogeneities and exceptions analysed.

Results exposed a consistent inequality between economic classes across all analyses, corroborating findings from previous studies of accessibility in São Paulo. The adoption of an individual-based approach allowed for the association between economic class and transport modes to be unfolded, revealing accessibility inequalities both within economic classes and amongst users of the same transport modes.

The analysis demonstrated that patterns of residence and workplace location for the different economic classes play an important role in the inequality of accessibility, corroborating Slovic et al's (2019) findings on the role of the core-periphery land use distribution of São Paulo. This is in-line with authors (Boisjoly et al., 2020; Slovic et al., 2019; Vasconcellos, 2018) who advocate for measures to address the typically peripheral location of low-income housing. This includes state-supported social housing initiatives, as well as incentives for other land use types (such as commercial and services) to locate in less-central areas of the city in order to increase the number of jobs and overall opportunities to underserviced communities. The need for public policies addressing land-use distribution patterns was also demonstrated by focusing on specific groups of individuals that have high mobility but do not necessarily have easy reach of opportunities.

The study also highlighted the need for an equity-oriented improvement of the public transport system of São Paulo. Results showed that inequalities related to transport modes reinforce and aggravate access inequalities across economic classes that originate from distinct location patterns. Individuals from upper economic classes present higher accessibility levels than their lower classes counterparts independent on transport mode. In addition, individuals from upper classes benefit from the highest accessibility amongst all public transport users, despite being their minority users. As such, from a transport justice perspective, São Paulo's public transport is not being effective in improving the accessibility conditions of individuals from lower income classes who are also disadvantaged by their residential locations, similarly to Pereira's (2019) findings on Rio de Janeiro.

Users of private motorised transport modes (cars and motorcycles) present the overall highest accessibility levels across all economic classes. The analysis also revealed relatively equitable levels of individual accessibility across economic classes amongst private transport users. This indicates that, at the individual level, private motorized transport improves space-time convergence and reduces inequality of access across users from different economic classes. This is an important, yet concerning, finding which points to a clear individual benefit to travelling by car or motorcycle which acts as an incentive for users to financially invest in this kind of transport, even those from lower economic classes. This is in line with the known upward trend in private transport use in Brazilian cities (Pereira, Warwar, et al., 2021), which aggravates existing issues of congestion, air pollution, and other negative externalities such as traffic accidents (Vasconcellos, 2018). These, in turn, are likely to most adversely affect individuals from lower economic classes who are most exposed to pollution and traffic due to longer commutes by bus, or depend on walking, bicycles and motorcycles for their commute (Vasconcellos, 2018).

Those findings suggest São Paulo's working population has self-organised on an 'individual road to equity'. In face of the lack of effective and equitable public transport system, disadvantageous residential location, and unequal distribution of opportunities, individuals are taking action to improve their own accessibility levels. The short-term result is the here observed reduction in accessibility inequality across economic classes among motorised transport users, albeit this also implicates a higher *within-class* inequality between those lower-class individuals who can afford a private vehicle and those who cannot. In the long term, however, this road will not lead to equity nor to sustainability. As such, higher motorized levels will be detrimental to the overall population and actions targeting collective sustainability and equity are urgently required.

The study demonstrated the applicability of IBAMs at a large-scale study area which provided detailed insights into the inequalities of access across the population of São Paulo at a fine level of detail that cannot be achieved by place-based methodologies. Although the approach adopted imposed compromises, the methodology proposed is coherent with time geographic theoretic principles and constructs. By computing accessibility levels at the individual level, and aggregating them *a posteriori*, the approach allows for results to be aggregated and visualised in different ways, adding flexibility to the analysis. This methodological framework opens avenues for a wider adoption of IBAMs to a broad range of applications, including the study of multiple social dimensions and intersecting inequalities, thus contributing to their wider use in academic research as well as practice.

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