Inequity in transit: Evaluating public transport distribution through accessibility measurements in São Paulo, Rio de Janeiro, Curitiba and Recife, Brazil

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Abstract

Increasing attention is given to public transport services in cities of the Global South as a tool to enhance social inclusion and support economic development. Against this background, developing and evaluating indicators that quantify the distribution of public transport services from a social equity perspective is essential. The aim of the study is, therefore, to assess the equity of public transport services in four metropolitan regions in Brazil (São Paulo, Rio de Janeiro, Curitiba and Recife) with two commonly used indicators of public transport provision. The first indicator measures proximity to rapid transit infrastructure (bus rapid transit, light rail and heavy rail stops with high frequency throughout the day), and the second measures accessibility to jobs by public transport. While simple indicators of proximity to public transport stops are most commonly used given their ease of operationalization and communication, accessibility to job indicators are more representative of the benefits provided to individuals by the public transport network. Combining these two indicators in one study provides a quantitative assessment of the socio-spatial distribution of public transport services in four large metropolitan areas in Brazil and the results demonstrate that lower-income households are disadvantaged in terms of public transport services in all four metropolitan areas. Furthermore, the results highlight the importance of quantifying accessibility by public transport, in addition to proximity to rapid transit, and thereby sheds light on the importance of developing openly available public transport schedules and geographic data. This study is of relevance to planners and researchers wishing to measure and evaluate public transport equity in the Global South.

Keywords: Accessibility evaluation; Equity; Public transport; Latin America

1 Introduction

Increasing attention is given to transport services and infrastructure in cities of the Global South as a tool to enhance social inclusion and support economic development and many international institutions are now stressing the importance of investing in transport. As such, the World Bank recently launched an initiative to increase accessibility to economic and social opportunities in an effort to reduce poverty (The World Bank, 2016). Public transport plays a key role to increase accessibility to opportunities, especially for low-income individuals (Hernandez, 2018). However, in rapidly urbanizing contexts, providing equitable public transport services is a significant challenge. Furthermore, the lack of data in the Global South poses an additional barrier to evaluate the provision of service from a spatial and social perspective. While previous research has been conducted in Latin America in relation to transport equity, no study has, to our knowledge, provided a quantitative assessment of the socio-spatial distribution of public transport services in multiple metropolitan regions in Brazil.

The aim of the study is, therefore, to assess equity in the distribution of public transport services in four large metropolitan regions in Brazil (São Paulo, Rio de Janeiro, Curitiba and Recife), with two commonly used indicators of public transport provision. The first indicator measures proximity to rapid transit (bus rapid transit (BRT), light rail and heavy rail stops with high frequency throughout the day), while the second measures accessibility to jobs by public transport. The study is conducted at the metropolitan level to reflect the employment opportunities available in the whole region and census tracts are used as the unit of analysis to obtain a fine-grained resolution. The indicators are further combined with income data to assess how transport services are distributed across different income groups. This study is of relevance to planners and researchers wishing to measure, evaluate and understand the socio-spatial distribution of public transport in the Global South.

2 Literature review

2.1 Public transport and (in)equity in Latin America

Large cities in Latin America have undergone rapid urbanization processes as well as sustained economic growth in the last two decades (Hidalgo & Huizenga, 2013). This rapid development has put significant pressures on urban transport infrastructure and land use, and most cities have not been able to respond to this rapidly growing demand in a coordinated manner. As a result, many Latin American metropolitan regions are now characterized by significant spatial and social segregation and an unequal distribution of infrastructure (Blanco, Lucas, Schafran, Verlinghieri, & Apaolaza, 2018; Keeling, 2008).

This poses significant challenges in terms of urban mobility and accessibility, especially for vulnerable populations. A few studies, conducted in different metropolitan regions in Latin America, found that low-income individuals typically experience lower accessibility to opportunities and public transport services (Bocarejo & Oviedo, 2012; Delmelle & Casas, 2012; Hernandez, 2018; Hernandez & Rossel, 2015). For example, in a recent study conducted in Montevideo, Uruguay, Hernandez (2018) showed that individuals residing in low-income areas experience a significantly lower level of accessibility to jobs and education opportunities than other individuals. Furthermore, they found that low-income individuals often travel longer times for the same distance, as they depend on active and public transport modes, which are slower and often less direct than private car travel. Similarly, in Santiago de Chile, Martínez, Hodgson, Mullen, and Timms (2018) found that greater travel times are needed to access opportunities from peripheral areas, where most of the social housing clusters are concentrated. Along the same line, Vasconcellos (2018) demonstrated that low-income individuals residing in São Paulo and Rio de Janeiro, Brazil generally travel longer times for essential trips given their home location and their dependence on public transport. Also, in terms of public transport coverage, Jaramillo, Lizarraga, and Luis Grindlay (2012) found that, in Santiago de Cali, Colombia, areas in the lower socio-economic strata are typically underserved in terms of public transport relative to their needs.

The lack of adequate public transport services and accessibility has tangible consequences on low-income households. Such situation often results in suppressed trips and activities as found in previous studies in Uruguay, Argentina, Chile and Brazil (Falavigna & Hernandez, 2016; Ureta, 2008; Vasconcellos, 2018). Namely, in São Paulo and Rio, low-income households were found to have higher immobility rates given the lack of adequate mobility options (Vasconcellos, 2018). Furthermore, to cope with the lack of mobility options, many low-income households opt for proximity as a strategy, which limits the number of opportunities (jobs, health, education, etc.) they can reach and afford (Blanco & Apaolaza, 2018). The lack of access to opportunities has broad consequences as demonstrated by Boisjoly, Moreno-Monroy, and El-Geneidy (2017): they found that in the São Paulo Metropolitan Region, the lack of accessibility to jobs by public transport is associated with higher probabilities of being informally employed for low-income individuals. Along these lines, a recent study in Buenos Aires, Argentina demonstrated how spatial structure and differential mobility can exacerbate existing socio-economic inequalities (Blanco & Apaolaza, 2018).

2.2 Transport equity

In both the Global South and the Global North, research has demonstrated that the provision of public transport services has significant impacts on individuals and that some populations are more likely to suffer from the lack of adequate public transport options (Falavigna & Hernandez, 2016; Lucas, 2012; Maia, Lucas, Marinho, Santos, & de Lima, 2016; Martens, 2016; Preston & Rajé, 2007). Equity issues are thus inherent to the provision of public transport services. Against this background, researchers have focused on how to define and assess equity in the distribution of transport investments (Golub & Martens, 2014; Lucas & Jones, 2012; Pereira, Schwanen, & Banister, 2017). Two questions arise when attempting to define and measure transport equity, as discussed by Pereira et al. (2017). The first one relates to what should be measured to evaluate the quality of the service provided from a social perspective. The second one is concerned with what constitutes a fair distribution of the service in a region.

With respect to the question of what should be measured, researchers argue that accessibility, broadly understood as the level of access to opportunities, should be considered to assess the distribution of benefits provided by transportation systems (Lucas, van Wee, & Maat, 2016; Martens, 2016; Martens, Golub, & Robinson, 2012; Pereira et al., 2017; van Wee & Geurs, 2011). Several authors build on Rawls' theory of justice to support the idea that accessibility is central to transportation justice (Martens, 2016; Martens et al., 2012; Pereira et al., 2017; van Wee & Geurs, 2011). Rawls' theory of justice identifies a set of *primary goods* that are essential to every citizen, and argues that institutions should play a role in the distribution of these goods to ensure that all citizens are equal (Martens, 2016; Pereira et al., 2017). Although Rawls does not identify accessibility as *a primary good*, Martens (2016) provides a strong argument for considering accessibility as such. Whereas Rawls defines *primary goods* as the set of goods that enable individuals to pursue their own life plans, Martens (2016) demonstrates that accessibility is essential to enable individuals to meet their needs, as it allows them to reach activities and opportunities.

Accordingly, given that accessibility is argued to be a basic good in the sense of Rawls' theory of justice, it should be distributed according to the principles of justice (Martens, 2016; Pereira et al., 2017). Furthermore, empirical research has demonstrated the impact of (lack of) accessibility, especially by public transport, on individuals. Namely, several studies have found a negative relationship between accessibility to jobs by public transport and unemployment (Kawabata, 2003; Matas, Raymond, & Roig, 2010; Sanchez, 1999).

With respect to what should be considered a fair distribution of services, researchers build on egalitarian theories to derive principles of justice. Egalitarian theories, such as Rawls' theory of justice, stipulate that all people should be treated equally (Lucas et al., 2016). Similarly, the capability approach suggests that all individuals should be provided with equal opportunities (Pereira et al., 2017). While this could suggest that the benefits of transportation systems should be equally distributed to all individuals, researchers emphasize that what matters is equality of opportunities. Since individuals inevitably have unequal opportunities in a society, given internal and external constraints, egalitarian theories suggest that an unequal distribution of transportation benefits should be considered to minimize inequality of opportunities (Martens, 2016; Pereira et al., 2017). In other words, it is argued that individuals that are more likely to have limited opportunities, due to financial, cultural, physical, or cognitive constraints, should be provided with higher levels of accessibility.

In sum, there is an agreement that a fair distribution of transport benefits should consider the distribution of access to opportunities. Furthermore, one of the main principles of justice highlighted by transportation researchers suggest that the level of access of disadvantaged populations should be maximized relative to the rest of the population to foster equity of opportunities.

2.3 Measurement of the distribution of public transport services

2.3.1 Proximity to rapid transit

The simplest geographic measure of public transport supply is a measure of proximity to public transport, which considers walking distance to public transport stops. Studies identify a walking distance buffer around public transport stops to identify areas that are served by public transport, considering a variety of thresholds typically ranging from 400 m to 1500 m (Blair, Hine, & Bukhari, 2013; Delmelle & Casas, 2012; Grengs, 2001). Using these buffers, researchers then calculate the proportion of the population or area that is covered by public transport. These measures directly represent service coverage, and are accordingly often used by researchers, public transport authorities and international institutions (Atlanta Regional Commission, 2016; Leadership Council of the Sustainable Development Solutions Network, 2015; Metrolinx, 2008; Singapore Land Transport Authority, 2013).

In the Latin American context, proximity to rapid transit (BRT, light rail and heavy rail stations) is generally measured to reflect access to an efficient, fast and reliable public transport service, given that regular bus service is often deficient in terms of travel speeds, reliability and frequency (Hidalgo & Carrigan, 2010; Vasconcellos, 2018). For example, Delmelle and Casas (2012) calculated the proportion of the population, grouped in six socio-economic strata, that is within walking distance (5, 10, 15, 20 minutes) of the new BRT network in Cali, Columbia. This allows assessing the coverage of the system in relation to the residential location of low-income individuals. Using a similar method, the Institute for Transport and Development Policy (ITDP) recently launched a large-scale analysis of the proportion of individuals near rapid transit for 25 urban areas around the globe to inform the debate on the quality and equity of public transport infrastructure in both OECD and non-OECD countries (Marks, Mason, & Oliveria, 2016).

2.3.2 Accessibility by public transport

Another increasingly used indicator of public transport service measures accessibility to destinations by public transport. Accessibility captures “the potential of opportunities for interaction” (Hansen, 1959, p. 73) and can be understood as the “ease of reaching land use given the transport system” (Levinson & Krizek, 2007, p. 44). In line with this definition, accessibility is contingent on both the spatial distribution of activities (land use component) and the characteristics of the transport network (transport component) that determines the travel time, distance and cost needed to reach these activities. While it is important to acknowledge that personal preferences and constraints also affect one’s accessibility, this study focuses on the land use and transport components.

To capture the ease of reaching destinations, many researchers use location-based accessibility metrics in public transport equity studies (Foth, Manaugh, & El-Geneidy, 2013; Golub & Martens, 2014; Grengs, 2010). This measure counts the number of opportunities that can be reached from a specific location by public transport using a gravity-based or cumulative-opportunity cost function, generally based on travel time. The gravity-based approach discounts opportunities as a function of their travel cost, while the cumulative-opportunity approach equally values all opportunities located under a specific cost threshold, while all other opportunities are ignored. Most researchers focus on employment opportunities as a proxy for the density of activities, although broader concerns have recently been introduced in equity studies, namely accessibility to food supply (Ferguson, Duthie, Unnikrishnan, & Waller, 2012), recreation sites (Delmelle & Casas, 2012) and health care services (Delmelle & Casas, 2012; Paez, Mercado, Farber, Morency, & Roorda, 2010). Accessibility indicators are typically measured using travel times obtained from openly available Google Transit Feed Specification (GTFS) data. They are increasingly used in transport practice in the Global North, namely due to the availability of GTFS data and computing resources (Boisjoly & El-Geneidy, 2017a; Proffitt, Bartholomew, Ewing, & Miller, 2017; Transport for London, 2006). Their use is although very limited in the Global South. One reason for this is likely the lack of available GTFS data, which has been found to be a significant barrier to the generation and implementation of accessibility measures (Boisjoly & El-Geneidy, 2017b; te Brömmellstroet, Silva, & Bertolini, 2014).

Nonetheless, a few studies have considered accessibility to destinations by public transport in equity studies in Latin America. Delmelle and Casas (2012) measured accessibility to hospitals, recreation sites and libraries based on the formal public transport network. Travel times were generated through a multimodal network developed in a geographic information system, assigning specific speeds to the trunk, feed and express routes of the system. This method requires extensive data manipulation and speed assumptions, but allows for a detailed assessment of accessibility. Bocarejo and Oviedo (2012) measured accessibility to jobs by public transport in Bogota, Columbia using generalized costs (travel time and affordability), and where the costs were calculated based on travel behaviour. While this approach provides a measure that better reflects actual travel times, it is conducted for a few selected zones only, and accordingly does not measure accessibility across the whole city. Pereira, Banister, Schwanen, and Wessel (2018) measured changes in accessibility following the public transport developments spurred by mega-events such as the Football World Cup and the Olympic games. Travel times were measured using the GTFS data provided by the federation of transport companies of the municipality of Rio de Janeiro.

Such data is, however, rarely available, and in this case, was limited to the municipality of Rio de Janeiro, thereby ignoring all jobs and individuals located outside the municipality boundaries. Overall, these studies contribute to a better understanding of how public transport allows individuals from different income groups to reach a variety of destinations. They also highlight the challenges associated with the development of comprehensive and detailed accessibility assessments in the Latin American context. The lack of widely available GTFS data in most metropolitan regions brings important limitations, either in terms of data generation and manipulation, or boundaries and scale.

As highlighted in previous work (Keeling, 2008; Oviedo & Titheridge, 2016), issues of transport, accessibility, poverty and social exclusion are still largely misunderstood in the Global South. This research complements the previous studies conducted in Latin America to address this gap by providing a quantitative assessment of accessibility by public transport and equity in four large metropolitan regions. The approach provides an important contribution to the accessibility literature as it uses GTFS data covering the entire metropolitan regions, and thereby assesses accessibility at the metropolitan level.

3 Area of study

Four metropolitan regions in Brazil are considered in this study: São Paulo, Rio de Janeiro, Curitiba and Recife. The characteristics of these regions are presented in Table 1. These cities were selected based on the availability of data and represent metropolitan regions of different scales in terms of population and rapid transit network. São Paulo and Rio de Janeiro are large metropolitan regions with more than 10 million inhabitants, and are characterized by extensive BRT and metro systems, with more than 300 kilometres and 260 stations. Conversely, Curitiba and Recife are smaller metropolitan regions (around 3 million inhabitants), with a rapid transit system composed mainly of a BRT network. In terms of spatial structure, Recife and Rio de Janeiro are coastal cities, with a large concentration of activities located by the seaside. In contrast, São Paulo and Curitiba are continental cities which follow a concentric distribution of activities. It is important to note that, while Curitiba has a large spatial extent (16,580 km^2), a large proportion of the metropolitan region is rural, with most urban areas concentrated in the centre of the region. It is important to note that informal jobs, which range from 32 % of the labor market in Curitiba to 41 % in Rio de Janeiro (Instituto Brasileiro de Geografia e Estatística, 2015), are not included in this study, since the data was not available. This limitation is discussed in the conclusion of the study.

Table 1: Characteristics of the metropolitan regions included in the study

	São Paulo	Rio de Janeiro	Curitiba	Recife
Population (million inhab.)*	19,136,063	11,784,888	2,866,058	3,555,431
Number of jobs*†	5,221,492	2,287,911	730,077	620,922
Metropolitan region area (km^2)	7,946	6,738	16,580	2,772
Urban area (km^2)	2,844	2,869	1,033	723
Urban census tracts (#)	28,837	19,346	3,752	4,348
RT Modes	BRT, HR	BRT, HR	BRT	BRT, HR
RT network length (km)	333	334	75	70
RT network stations (#)	260	261	119	61
Average commute time (min)**	42.6	42.8	32.1	34.9

RT: Rapid transit, BRT: Bus rapid transit, HR: Heavy rail
*number of jobs and population in urban areas only (which represents above 99% of the population)
†formal jobs in the private sector
**Data source: Pereira and Schwanen (2013)

3.1 Data and methods

3.2 Area and unit of analysis

The analysis encompasses all municipalities within the metropolitan regions, using census tracts as the unit of analysis. Since the study focuses on urban public transport, we only included census tracts characterized as urban, as defined by the *Institutio Brasileiro de Geografía e Estatistíca* based on municipal law and observation of land use. However, due to computational, time and financial limitations, we had to limit the number of points for which we generated the measures of accessibility to jobs by public transport. To do so, the following approach was undertaken: for each metropolitan region, a 1.5 X 1.5 km^2 grid was laid over the metropolitan region and intersected with the urban census tracts. The resulting grid cells were then used as the unit of analysis for the measures of accessibility to jobs by public transport, calculating travel times between the centroids of the grid cells. Accordingly, an accessibility value was calculated for each grid cell centroid (more details on the accessibility calculations are presented in section 4.3.2). The results were then interpolated using an inverse distance weighted approach to assign an accessibility value to each census tract. More specifically, the accessibility was derived for each census tract centroid based of the four nearest neighbors (grid cell centroids). A weighted average of the four neighbors was computed, the weight being defined as inversely proportional to the distance. In other words, closer grid cells were given higher weights than further away grid cells.

3.3 Data

To generate the proximity to rapid transit indicators, three types of data were collected from various sources. The location of rapid transit stops was obtained from ITDP, that keeps an up-to-date map of Brazilian operational and under construction rapid transit corridors based on information from municipal, state and federal-level public institutions. All stations from rapid transit corridors that were operational at the time of the study (March 2018) were included in the dataset. Rapid transit corridors include BRT and LRT that attain the BRT Basics as per ITDP's BRT Standard (ITDP, 2016) and heavy rail that provide a high-frequency (20 minutes in both directions) throughout the day (6 am to 10pm) and operate entirely within a single built-up urban area[1]. Note that the ferry in Rio de Janeiro is also considered a rapid transit mode due to its frequency and operation characteristics.

With respect to the measures of accessibility to jobs by public transport, travel times were collected through the Google Maps Distance Matrix API (Google Maps, Accessed February, 2018), while the employment data was obtained from the *Relação Anual de Informações Sociais* from the *Ministério do Trabalho e Previdência Social (Ministério do Trabalho e Previdência Social, 2010).* The Google API returns the travel time by public transport (including rapid transit services as well as regular bus services), in minutes, of the fastest route requiring fewer transfers for each origin-destination pair. The travel time includes the access time, the in-vehicle time, the transfer time and the egress time. It is important to note, however, that the waiting time before departure is not counted in the Google API, which assumes that individuals are flexible with their departure time. Generating the travel times directly with the GTFS data would have allowed more customization of the travel time calculations, but such data was not available. To our knowledge, only one study used detailed GTFS data in Latin America and such study was conducted at the municipal level (Pereira et al., 2018). For the purpose of this study, travel times were measured at

[1] More details about the ITDP definition of rapid transit stations can be found in the following report: https://www.itdp.org/wp-content/uploads/2016/10/People-Near-Transit.pdf

peak hour (7 am departure time), as done in previous studies (Boisjoly et al., 2017; Pereira et al., 2018). A 7 am departure time was set to reflect commuting behaviour in Brazil, based on the peak hour in the São Paulo Metropolitan Region (METRO-SP, 2008).

Data on household income, aggregated at the census tract level, was obtained from the 2010 census (Instituto Brasileiro de Geografia e Estatistica, 2010). Note that the income data is not available at the individual level and that the household data does not contain the size of the households. The number of households within each income category is provided for each census tract. In this study, four household categories were used based on the minimum wage (MW) in Brazil:

- (i) income below half of the minimum wage (low-income households)
- (ii) income between half the minimum wage and minimum wage (low-income households)
- (iii) income between 1 and 3 times the minimum wage (medium-income households)
- (iv) income three times above the minimum wage (high-income households)

These income categories are used in Brazil in the implementation of social policies. Note that the first two groups are both referred to as low-income households in this study.

3.4 Methods

Two measures of provision of public transport services were developed in this study. As highlighted in the literature review, accessibility to opportunities is a key measure for assessing the provision of public transport services from an equity perspective. This study focuses on accessibility to jobs, by public transport, to reflect the performance of the public transport system relative to location of activity centers, as typically done in cities of the Global North (Boisjoly & El-Geneidy, 2017a). In addition to this measure of accessibility, a measure of proximity to rapid transit was generated. While this measure is less theoretically sound in terms of the benefits provided by the public transport system, it is commonly used in practice, especially in the Global South (Atlanta Regional Commission, 2016; Leadership Council of the Sustainable Development Solutions Network, 2015; Marks et al., 2016; Metrolinx, 2008; Singapore Land Transport Authority, 2013). The generation of the two measures in the same study allows shedding light on the contribution of accessibility to opportunities indicators, in a context where a lot of institutions rely on proximity to rapid transit indicators.

3.4.1 Proximity to rapid transit

Proximity to rapid transit was measured using a buffer approach. Two types of buffers were generated around the rapid transit stations. The first one is measured based on the airline distance (circular buffer), as commonly done in practice (Marks et al., 2016). The second one uses the street network distance (street buffer) to reflect walking access to the rapid transit stations. The street networks were obtained from OpenStreetmap and connectivity was corrected for. While the airline buffer is more commonly used due to simplicity reasons and lack of data, especially in the Global South, the second one more realistically represents the access that individuals have to those stations by walking. In both cases, a 1 km buffer was used to reflect the distance individuals are willing to walk to access rapid stations, representing a 10-15 min walking distance. While shorter distances (400m) are typically used for regular transport stops (Blair et al., 2013; Grengs, 2001), research shows that individuals are willing to walk longer distances to access rapid transit service (El-Geneidy, Grimsrud, Wasfi, Tétreault, & Surprenant-Legault, 2014; Lachapelle & Noland, 2012). This is also consistent with Delmelle and Casas (2012) who considered a variety of thresholds ranging from 0.375 m (5 min) to 1.5 km (20 min) to assess proximity to BRT in Cali, Columbia.

To calculate the number of households living in proximity to transit, all households in a census tract for which the centroid falls within the 1 km buffer area are counted. One measure is generated for the circular buffer and another one for the street buffer. The analysis is conducted across all four income groups.

3.4.2 Accessibility to jobs by public transport

A cumulative-opportunity measure was used to measure accessibility to jobs by public transport. This measure counts the number of jobs that can be reached from each census tract using public transport, under a specified travel time threshold. This measure, which is most commonly used in practice, has been found to accurately represent the relative accessibility experienced across a metropolitan region and to be more adequate for planning purposes (Boisjoly & El-Geneidy, 2016). Furthermore, such measure is highly correlated with gravity-based measures (El-Geneidy & Levinson, 2006), while being easier to communicate and to interpret (Geurs & van Wee, 2004). It is calculated as follows:

$$A_i = \sum_{j=1}^{n} O_j f(C_{ij}) \qquad (1)$$

$$f(C_{ij}) = \begin{cases} 1 \text{ if } C_{ij} \leq t \\ 0 \text{ if } C_{ij} > t \end{cases} \qquad (2)$$

where A_i is the accessibility at point i to all jobs in grid cell j, O_j the number of jobs in grid cell j and $f(C_{ij})$ the weighting function with C_{ij} being the time cost of travel from the centroid of i to centroid of j and t, the travel time threshold. As mentioned above accessibility to jobs was measured using a 1.5X1.5 grid cell unit[2]. The jobs are counted if they are located within the travel time threshold. In this study, a travel time threshold of 60 minutes is used for São Paulo and Rio de Janeiro, as done by Pereira et al. (2018) in Rio de Janeiro. While many studies in the Global North use 45 minute thresholds, large Brazilian metropolitan areas typically have longer commute times than other metropolitan areas (Pereira & Schwanen, 2013). As such, the average travel time by public transport in the SPMR is 67 minutes (METRO-SP, 2008). Given that Curitiba and Recife have significantly lower commute times than São Paulo and Rio de Janeiro (see Table 1), a 45 minute threshold was used for these two metropolitan regions.

3.4.3 Equity analysis

To assess the equity of public transport services, this study compares both indicators (proximity to rapid transit and accessibility to jobs) across the four income groups defined above. Equity is defined here based on the concept of vertical equity, which suggests that the distribution of public transport services should favour population groups with greater needs (Delbosc & Currie, 2011; van Wee & Geurs, 2011). This is in line with the theoretical justifications discussed in the literature review. Given that low-income households are more likely to depend on public transport, household income is used to identify population groups with greater needs. Accordingly, an equitable distribution of public transport services would be reflected in low-income groups having a higher provision of public transport services. Other factors, such as gender and age, are relevant to transport equity analyses. However, given the data availability, only income is considered in this study.

[2] In the case of São Paulo, accessibility by public transport was measured using the Transport Analysis Zones (633 in the whole metropolitan region) as this data was available from a previous study.

4 Results

4.1 Households near rapid transit

The proportion of households, in each income category, that is near rapid transit is presented in Figure 1. The darker bars represent the proportion of households residing within 1 km of a rapid transit station using street distance, while the lighter bars represent the results for the 1 km circular buffer. Interestingly, we see that both buffers yield consistent trends in all four metropolitan areas, although the circular buffer tends to overestimate the proportion of households residing near rapid transit. It is accordingly important to consider this discrepancy when selecting an indicator.

Nonetheless, for both indicators, we observe a common trend in São Paulo, Rio de Janeiro and Curitiba: a lower proportion of low-income households (below ½ MW and between ½ MW and 1 MW) live within 1 km of a rapid transit station, while higher-income households (above 3 MW) are located in much greater proportion near rapid transit. This shows an inequitable distribution of rapid transit stations across income groups, especially since low-income populations are more likely to depend on public transport for long commute trips. With respect to Recife, we observe a lower variation between income groups. While low-income households exhibit similar proportions as in the other metropolitan regions, medium-income households (between 1 and 3 MW) and higher-income households (above 3 MW) yield much lower proportions. Interestingly, higher-income households (above 3 MW) have a lower proportion of households located close to rapid transit.

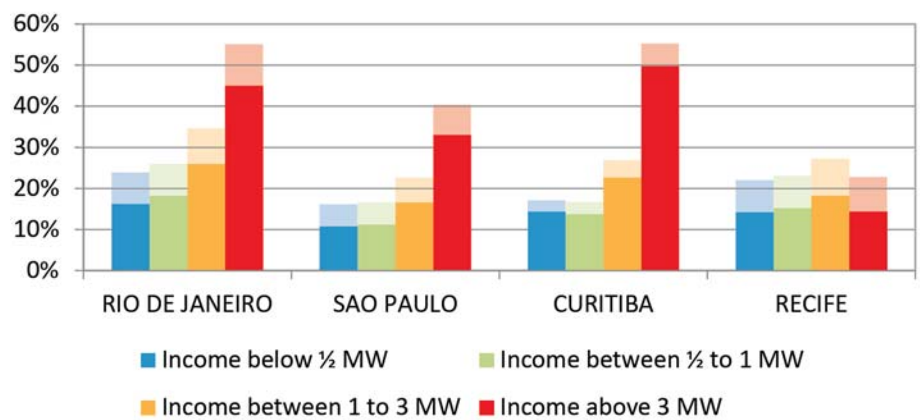

Figure 1: Proportion of households near transit by income category. Street buffers (dark). Circular buffers (light)

Figure 2 presents the buffer areas and predominant household income of each census tract to better understand the spatial patterns associated with these results. For each census tract, the predominant income corresponds to the income category with the greatest number of households. It is clear from Figure 2 that buffer areas are mainly comprised of higher-income census tracts in São Paulo, Rio de Janeiro and Curitiba, while in Recife, a large proportion of high-income households live away from rapid transit, namely by the sea (to the east). High-income household also concentrate near to the sea in Rio de Janeiro (to the south), but this area is served by rapid transit. It is also interesting to note that Rio de Janeiro has an overall greater proportion of households near rapid transit across all income groups, likely due to the presence of rapid transit stations across most of the densely populated areas.

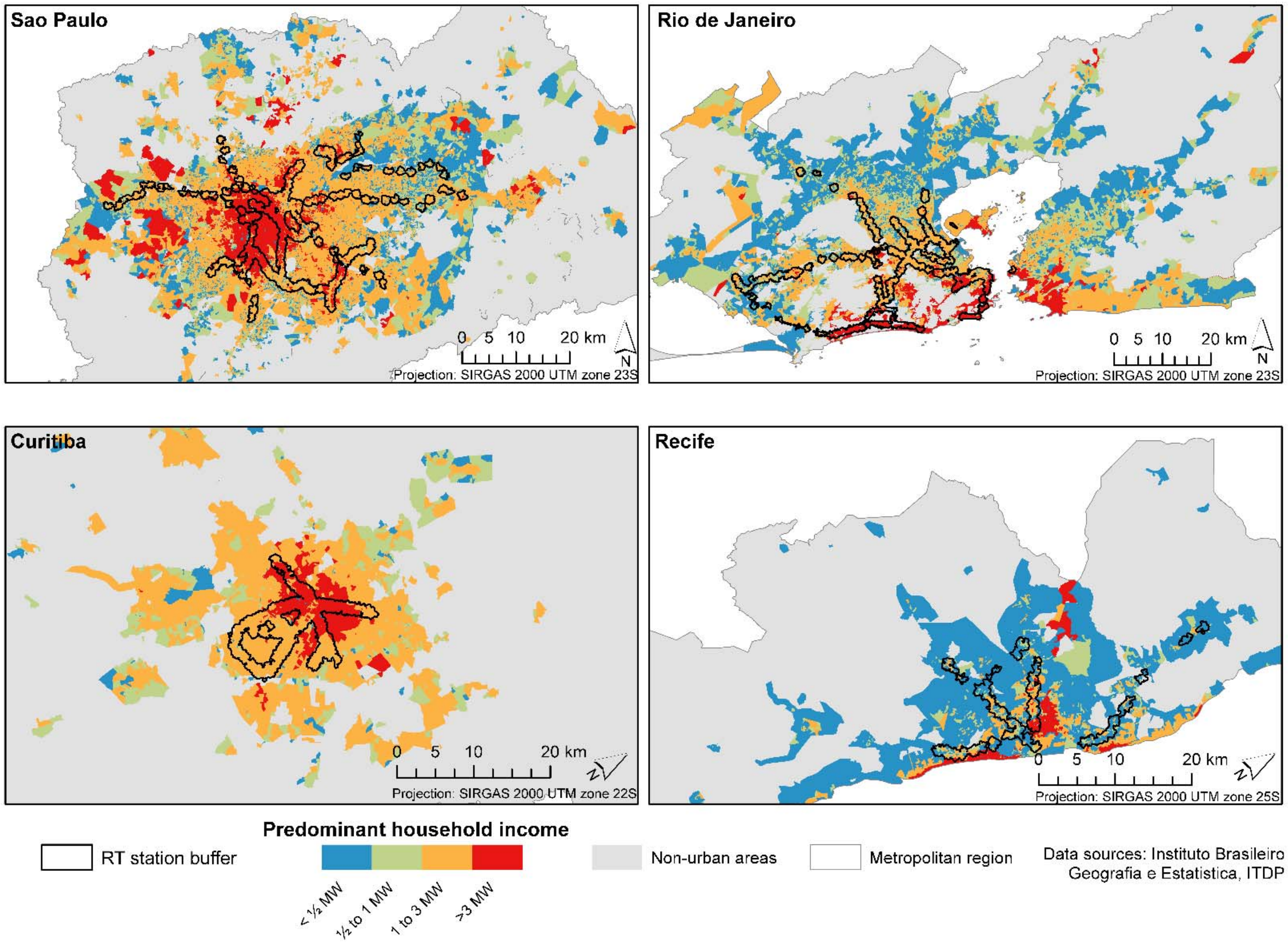

Figure 2: Predominant household income and rapid transit station street buffers

4.2 Accessibility to jobs by public transport

Figures 3 and 4 present the accessibility to jobs and predominant household income in all four metropolitan regions. The accessibility is expressed as the proportion of all jobs located in the metropolitan region. For example, an individual that can reach 1,000,000 of the 5,221,492 jobs in São Paulo would have an accessibility of 19%. In all four metropolitan regions, census tracts located near the centre of the metropolitan region typically exhibit higher levels of accessibility. Similarly, many census tracts with predominantly high-income households are located in the centre. Conversely, lower-income households tend to be located away from the centre, where accessibility is lower. Furthermore, especially in São Paulo and Rio de Janeiro, for the same distance to the centre, higher accessibility is observed near the rapid transit lines. These areas are also characterized by a high density of predominantly high- and middle-income household census tracts. In Curitiba and Recife, the relationship between rapid transit lines and accessibility patterns is less visible, likely due to the smaller size of the metropolitan region resulting in shorter commute times on average (Pereira & Schwanen, 2013). Regular busses are likely to yield similar travel times given the shorter commute and reduced congestion. Nonetheless, the results overall depict a clear trend in all four metropolitan regions: census tracts with predominantly low-income households typically exhibit lower levels of accessibility compared to other census tracts.

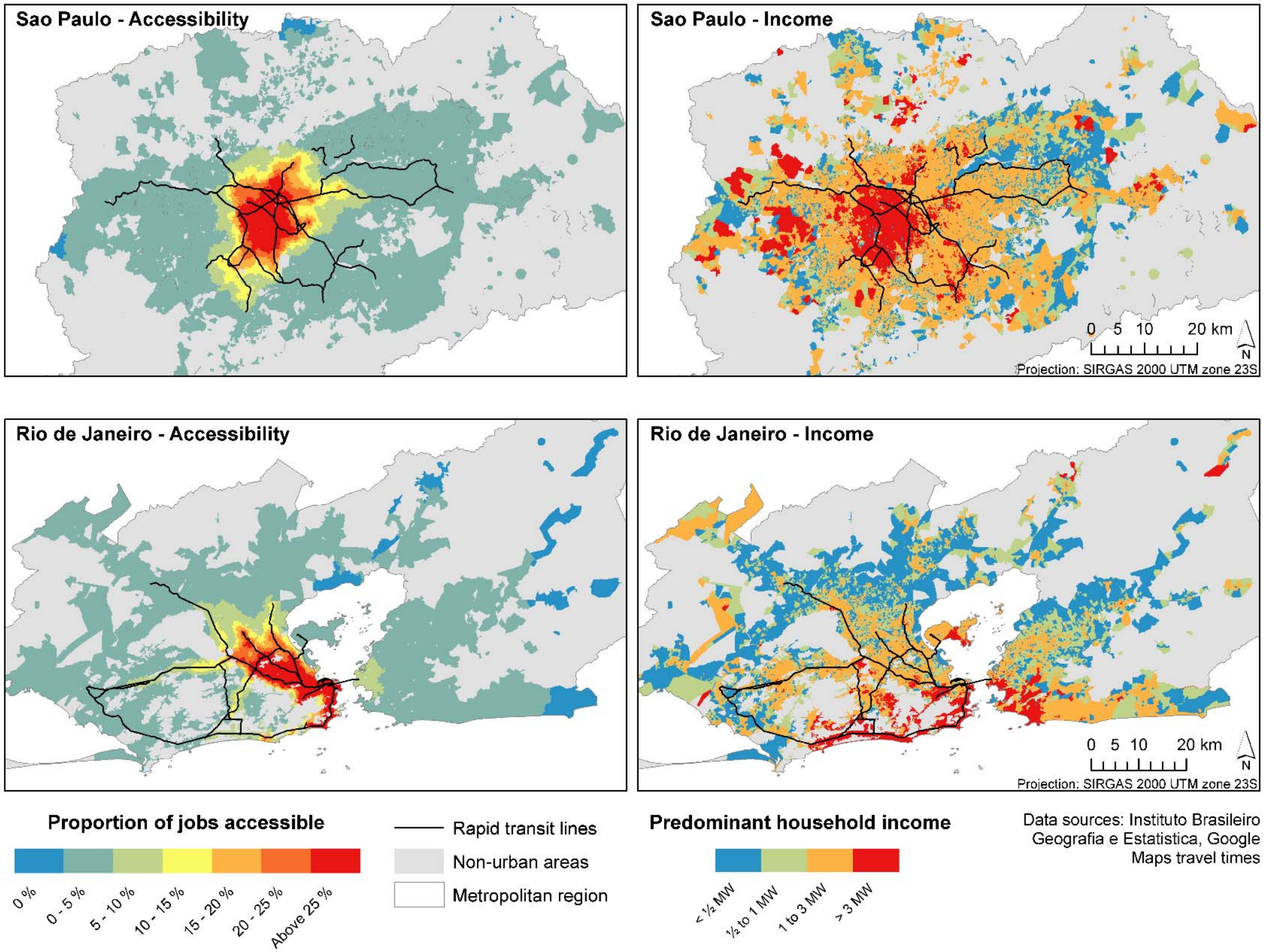

Figure 3: Accessibility to jobs by public transport and predominant household income in the São Paulo and Rio de Janeiro Metropolitan Regions

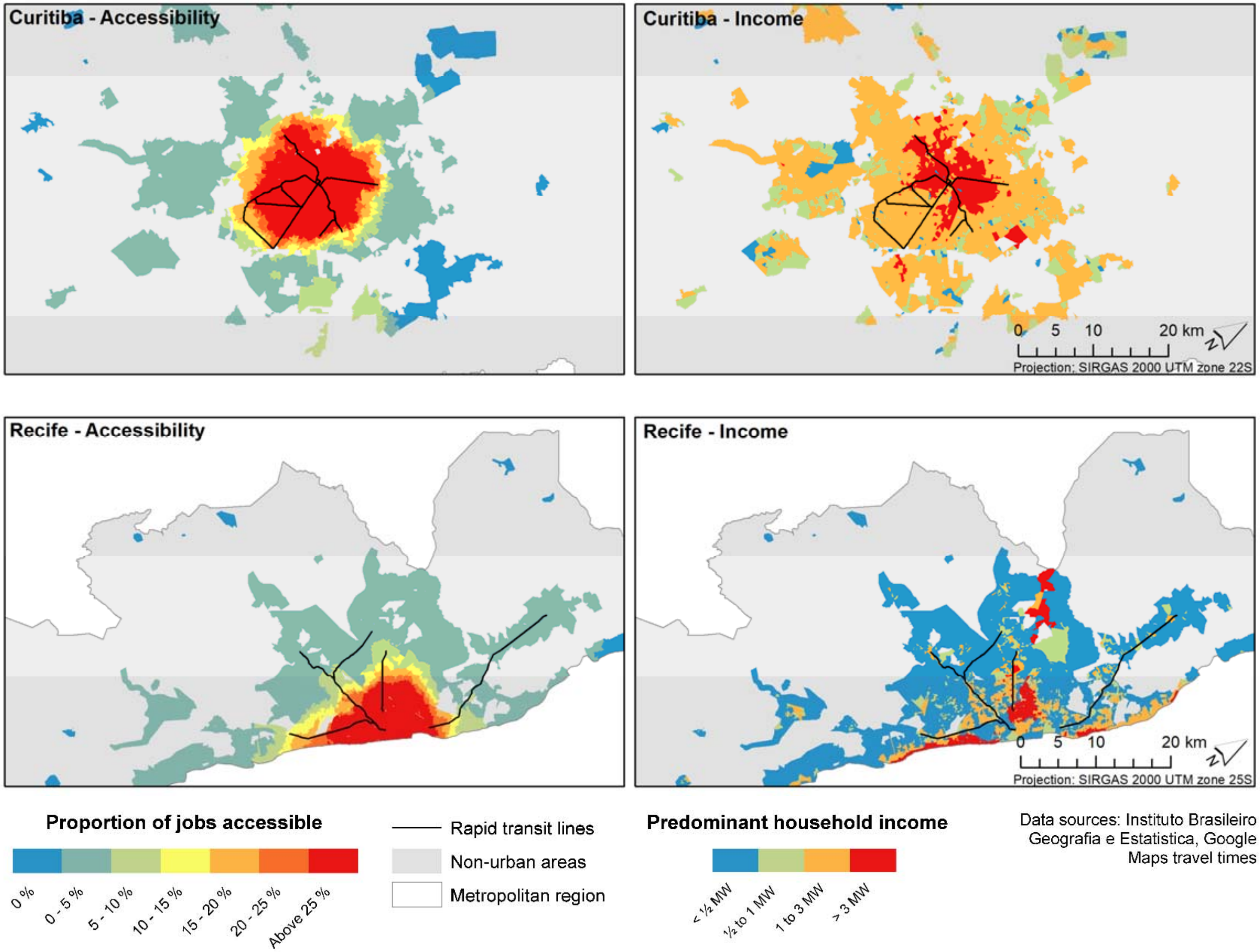

Figure 4: Accessibility to jobs by public transport and predominant household income in the Curitiba and Recife Metropolitan Regions

The distribution of accessibility across income groups is further explored by assessing the proportion of households that experience low and high accessibility for each income group. The level of accessibility is divided into four quartiles, to reflect the relative accessibility of each census tract relative to the metropolitan region. For each metropolitan region, the 25% census tracts with the lowest accessibility levels are grouped in the fourth quartile, while the 25% census tracts with the highest accessibility level are grouped in the first accessibility quartile. The proportion of households in each accessibility quartile is then calculated for each income group. The results are displayed in Figure 5. For example, in São Paulo, we observe that around 35% of the lowest-income households (<1/2 MW) experience the lowest level of accessibility (quartile 4), whereas only 11% of them experience the highest level of accessibility (quartile 1). Conversely, only 9 % of the high-income households (>3MW) experience low accessibility (quartile 4), whereas 56% of them are in the highest accessibility quartile (1). The results are consistent across all income categories: in a nutshell, in São Paulo, a lower household income is associated with a larger proportion of households in the lowest accessibility quartile and a lower proportion of households in the highest income category. Looking at the four metropolitan regions, the results are striking: the same trend is present across all four metropolitan regions, with a higher proportion of low-income households being in the lowest accessibility quartile and conversely for high-income households. These results suggest that all four metropolitan regions are characterized by an inequitable distribution of public transport services.

Another way to evaluate the equity in the distribution of accessibility is by looking at the household-weighted average accessibility, presented in red in Figure 5. The average accessibility of all households, of households near rapid transit stations and of households not near rapid transit are presented. For example, in São Paulo, the lowest-income households near rapid transit can access on average 10% of all jobs in the metropolitan region, while the lowest-income households not near rapid transit can only access 2% of the jobs on average. The results of the circular buffer are used here to reflect the most commonly used indicator of proximity to rapid transit in the Global South. Commencing with the average accessibility of all households, we observe that lower-income households experience, on average, lower accessibility to jobs by public transport in all four regions. The results thereby confirm that lower-income households are typically disadvantaged in terms of public transport services.

The results also hold when looking only at households near rapid transit (or only at households not near rapid transit). In other words, low-income households living near rapid transit nonetheless experience lower accessibility than high-income households living near rapid transit. Most notably, in the case of Recife, high-income households located away from rapid transit experience, on average, higher accessibility than low-income households near rapid transit. Furthermore, while the proportion of households living in proximity to rapid transit was similar across all income groups (and even lower for high-income households – see Figure 1), the accessibility results depict a highly inequitable picture. The concentration of high-income households near the city center and along the sea side, where the concentration of jobs is higher, likely explains the high accessibility experienced by high-income households, regardless of the presence of rapid transit stations.

These results highlight that not all rapid transit stations offer the same level of accessibility, and that the use of proximity to rapid transit indicators is limited in capturing the benefits provided by the public transport systems. While this study does not specifically assess the contribution of rapid transit systems on accessibility to opportunities, future research could build on the indicators developed in this study to explore this relationship.

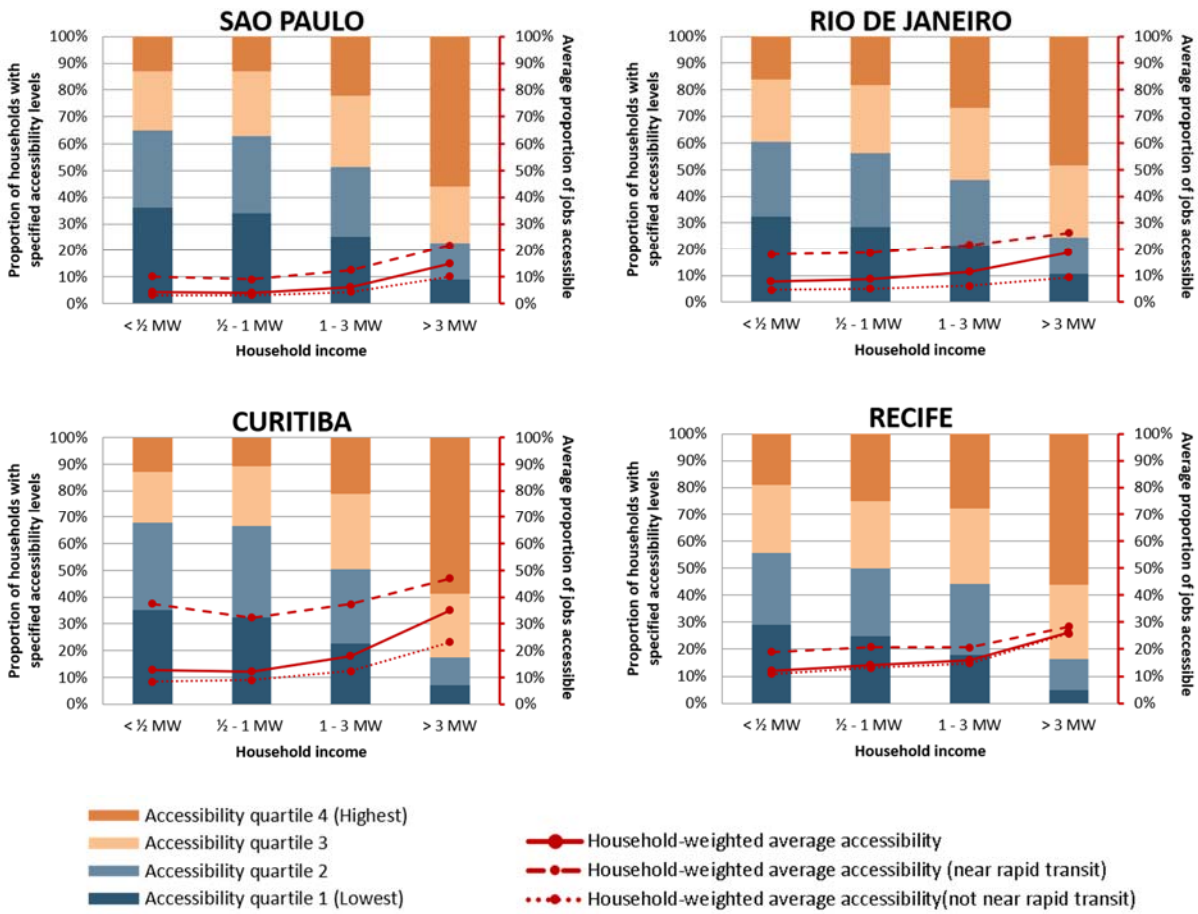

Figure 5: Proportion of households in specified accessibility quartile and household-weighted average accessibility, by income category

5 Discussion and conclusion

This study examined the socio-spatial distribution of public transport services in São Paulo, Rio de Janeiro, Curitiba and Recife, Brazil. The results show a clear trend of inequitable public transport provision in all four metropolitan regions: (i) a lower proportion of low-income households (below ½ MW and between ½ and 1 MW) live near rapid transit compared to higher-income households and (ii) a greater proportion of low-income households experience lower accessibility to jobs by public transport. While the analysis only includes four metropolitan areas, it is likely that the results apply to other regions in Brazil, and more broadly in Latin America, as similar socio-spatial segregation and transport policies are present (Blanco et al., 2018). Also, by investigating four metropolitan regions of different scales, the study demonstrated that the results are not only limited to major metropolitan regions, but also to smaller regions. Finally, the results are consistent with previous research which found low-income households to be largely disadvantaged in terms of public transport service and accessibility in Latin American metropolitan regions (Hernandez, 2018; Jaramillo et al., 2012). Building on the results from this study, future research could adopt a comparative case study approach to investigate the specific factors that contribute to inequity in public transit provisions and potentially identify barriers and opportunities to support a more equitable distribution of accessibility to opportunities.

Accessibility to opportunities by public transport, as measured in this study, can be improved in two ways: (i) improving public transport services, and (ii) bringing origins and destinations closer. Regarding public transport services, the development of rapid transit that serve peripheral area is likely to have a significant impact on the accessibility of low-income populations, as highlighted in our study. However, as also shown in our study, proximity to rapid transit is not sufficient to ensure high levels of accessibility among low-income households. The findings show that peripheral areas located near rapid transit have significantly lower accessibility than central areas located near rapid transit. This is likely explained by the concentration of employment opportunities in central areas. Accordingly, more efforts in bringing destinations closer to origins may support a more equitable distribution of accessibility. In this regard, Martínez et al. (2018) demonstrate how the social housing policies in Santiago de Chile, together with deficient transport investments, led to transport disadvantage among vulnerable individuals. In light of these findings, considering accessibility to jobs and services in social housing policies and transport investments would help bridge the gap in accessibility. Another key strategy is to support the decentralization of formal employment opportunities, given that formal job opportunities are mainly located in central areas in most large metropolitan regions in Latin America (Blanco et al., 2018; Boisjoly et al., 2017). A previous study found that the distribution of formal jobs is highly correlated with the distribution of informal jobs in Rio de Janeiro (Pereira et al., 2018). While it is not possible to conclude on the causality of this relationship, it is likely that the decentralization of formal jobs can also contribute to the decentralization of jobs in the informal sector.

As there are multiple governance and political challenges in implementing such land use and transport changes (Vasconcellos, 2018), the development of indicators is an important tool to inform the debate. Indeed, previous research has demonstrated the importance of accessibility indicators to support decision-making and improve the quality of public transport systems in helping individuals to reach their destinations (Boisjoly & El-Geneidy, 2017a; Handy, 2008). In line with this, our study demonstrates the contribution of accessibility indicators in evaluating equity in public transport services and contributes to the literature on equity and accessibility in Latin America by providing some improvements to previous methodologies. Namely, a fine-grained analysis was conducted at the metropolitan level using tools and data that can be found in the Global South. While a Google API was used in this study, openly available GTFS data would allow a broader implementation of accessibility indicators (Boisjoly & El-Geneidy, 2017a; te Brömmellstroet et al., 2014). Indeed, the monetary cost associated with the use of the Google API may be an important barrier for researchers or practitioners. In this regard, the study stresses the importance of developing GTFS data and making them fully accessible.

There are some limitations to this study. The first one is that only jobs in the formal sector are included in the analysis, since informal jobs were not available for all four metropolitan regions. However, as highlighted by Pereira et al. (2018), the spatial distribution of formal and informal jobs is highly correlated at the traffic zone level in Rio de Janeiro. This is likely similar in other metropolitan regions. Furthermore, formal jobs typically require a longer commute (Motte, Aguilera, Bonin, & Nassi, 2016), and are thus more likely to be accessed by public transport. Jobs in the public sector are also excluded from the analysis, as the location data was not reliable. This study therefore assumes that jobs in the public sector have a similar distribution to jobs in the private sectors. Further studies should be conducted to provide a better understanding of how jobs in the public sector are distributed across the region, and thereby identifying how it affects accessibility patterns. Along the same line, the current study does no distinguish between the types of job (qualifications, salary, etc.). This could be taken into consideration in future research. Future studies could also be developed to account for spatial competition, as done by Merlin and Hu (2017) and Allen and Farber (2019) in the North American context. Such measures are especially relevant to compare the levels of accessibility across metropolitan regions (i.e.: are low-income households better served in Curitiba than Recife?) and to explore the effect of competitive accessibility on labour outcome. Another avenue for future research would be to look at different opportunities, such as healthcare services and local amenities. A second limitation is the reliance on Google Maps travel time. Since it is proprietary data, we do not know the exact algorithm behind the calculation of travel times. Nonetheless, the Google Maps Distance Matrix API was used in previous studies and shown to be consistent with mode choice data for example (Boisjoly & El-Geneidy, 2016). Another important limitation, as in most accessibility studies, is that the quality of service, including reliability and cleanliness of vehicle for example, is not accounted for in this research. Furthermore, affordability and walking access and egress conditions are not taken into account. Since lower-income areas are more likely to have a lower quality of service, higher budget constraints, and more difficult access conditions (safety issues, presence of important slopes, etc.) (Vasconcellos, 2018), our study likely underestimates their accessibility relative to the rest of the population, and thus underestimates the inequity of public transport provision. Nonetheless, the study provides a reliable comparative assessment of public transport equity based on travel time schedules across four metropolitan regions in Brazil, and is of relevance to researchers and planners wishing to contribute to the development of more equitable public transport systems in Latin America and in the Global South more generally.

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