



Modal Accessibility Gap in Curitiba (Brazil). Dynamic Analysis Considering Time and Spatial Variations

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Abstract

This paper analyzes the accessibility of Curitiba, Brazil, by combining high-detail, big-data-informed automobile dynamic distance matrices from TomTom Traffic Stats and a bus network database - GTFS data - provided by the Curitiba City Council. Accessibility is measured dynamically, considering the changing conditions of congestion levels and bus frequencies, along with the daily variation of mobility patterns. The accessibility gap between private and bus modes is estimated, and its daily variation is analyzed regarding its spatial and temporal distribution. This study identifies places with greater public transport supply deficiencies and locations with the greatest needs for public transport improvements, suggesting priority intervention areas to improve the accessibility of the population while promoting a shift toward more sustainable transport modes. The outcomes show the relative advantage of cars versus buses and that a higher portion of Curitiba's population lives in areas with high accessibility gaps.

Keywords Dynamic accessibility · Modal accessibility gap · Spatiotemporal transport dynamics · Sustainable urban mobility · Global south · Curitiba

Introduction

Metropolitan areas are complex spaces where transport infrastructures have become the main structuring physical elements (Ascher, 1995, 2010; Bertolini, 2017), and where accessibility is a crucial element to ensure high levels of quality of life. Accessibility is defined as "the extent to which the land use-transport system enables individuals to reach activities or destinations using a (combination of) transport mode(s)" (Geurs and van Eck, 2001: 36). Combining land use and transport elements, accessibility has had a quantitative, applied nature since its first definitions (Hansen, 1959), to seek applicability in planning.

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In recent years, different authors have advocated the use of accessibility indicators in the search for more sustainable territorial planning (Bertolini et al., 2005), which avoids long and motorized journeys, as well as a change towards more sustainable modes, such as public transport. However, we come from a tradition of car-oriented city planning, which entails an advantage of cars over other modes. To reverse this planning paradigm it is necessary to develop studies that compare the accessibility provided by different modes of transport, providing instruments to identify vulnerable areas, with less supply of sustainable transport alternatives. Thus, the main objective of this study is to evaluate what is known in the literature as the accessibility gap, comparing accessibility by car with accessibility in public transport, using the city of Curitiba (Brazil) as a case study.

There are several contributions to the literature made in this work. On the one hand, the accessibility of the most representative modes of travel in Curitiba is compared: the private vehicle and the bus. Most accessibility analyses have focused on one transport mode (Condeço-Melhorado et al., 2014; Hull et al., 2012; Silva & Larsson, 2018). However, comparing various transport modes and their accessibility conditions is necessary to understand modal choices and transport-related environmental sustainability (Gil, 2014; Kwok and Yeh, 2004). Comparing the balance or imbalance between transport modes is also fundamental to revealing diverse social implications, evaluating the constraints and disadvantages of those who cannot choose between transport modes, and evaluating social equity and cohesion (Carpio-Pinedo, 2019; Golub and Martens, 2014; Kawabata and Shen, 2007a; Martens, 2016; Pizzol et al., 2021).

On the other hand, we adopt a dynamic approach to measure accessibility. The measures of accessibility set a common framework to integrate land use and infrastructure, but both urban activities and transport conditions change throughout the day and week. Offices, shops, and schools open and close; buses and trains have certain operating hours and changing frequencies, and road congestion varies throughout the day. A dynamic approach to accessibility is thus necessary. This work considers road congestion levels and bus frequencies at every hour of a typical working day when measuring accessibility. The study relies on high-detail, big-data-informed automobile dynamic distance matrices from TomTom Traffic Stats and a bus network database from GTFS provided by the Curitiba City Council. Furthermore, using official data from Curitiba's mobility survey, this study considers the hourly number of persons reaching a destination as a proxy to measure the dynamic nature of activity levels within the city and therefore the changing attractiveness of places throughout the day. To the best of our knowledge, this is the first time that a study on the accessibility gap incorporates the variation in the activity levels of different locations. Most studies focus on the analysis of the accessibility gap for a specific time of the day. Some studies look at differences between peak and off-peak periods, but activities remain stable and only the level of service of transport modes varies. However, if we want to fully represent the dynamic nature of accessibility, we must use data sources that represent the daily variation of population at destination areas. For example, an industrial area may have high activity levels during working hours and less activity during rest periods. In our work, we allow the importance of accessing

destinations to change throughout the day by incorporating the mobility patterns of citizens in the formulation of the accessibility indicator.

Finally, this paper analyzes the accessibility conditions in a South American city: Curitiba (Brazil). As in many other fields, academic literature on transport geography in the Global South has not been as profuse as that on European and North American cities (Bocarejo et al., 2016). Analyzing Curitiba helps fill that gap and implies an assessment of a land use-transport model that has been endorsed as a reference for developing cities all over the world. Since the 1970s, transport infrastructure has conditioned Curitiba's urban growth: planning documents only allow high-density developments next to high-capacity bus corridors to stimulate ridership and minimize negative automobile outcomes. Curitiba's public transport system – based on bus-rapid transit (BRT) schemes – ensures almost the same passenger capacity and operating speeds as the light rail mode, together with convenient and safe stops that are key to attracting potential users.

The following section provides a literature review on dynamic accessibility analysis (section "[Dynamic Accessibility and new data sources](#)"), the measurement of the accessibility gap (section "[The accessibility gap](#)"), and the Curitiba's social and transport context (section "[Latin America and the case of Curitiba](#)"). Section "[Methodology](#)" presents the methods and data sources used in this study, and the outcomes are analyzed in section "[Outcomes](#)". Finally, section "Discussion and Conclusions" is devoted to discussion and conclusions.

Literature Review

Dynamic Accessibility and New Data Sources

As a key concept in land use and transport planning, accessibility faces the challenge of increasing its temporal variation detail (Geurs and van Wee, 2004). Until recent times, and probably due to data availability and processing limits, most accessibility studies have been 'static,' like a frozen picture. However, people's experience of accessibility is 'dynamic,' and this dynamism comes from the transport side and the land-use or activities included in accessibility formulation. Accessibility is conditioned by the destination's opening hours, levels of crowding, transport service timetables, road congestion, personal constraints, and other changing determinants (Fajardo-Magraner et al., 2023).

Regarding automobile accessibility, road congestion has been one key factor where the dynamic approach is crucial. GPS tracking and data capture make it possible to detail real car speeds compared to free-flow speeds, including temporal disaggregation (Moya-Gómez and García-Palomares, 2017). Other factors might be included, such as the time to find a parking space, which also varies throughout the day (Salonen & Toivonen, 2013). Regarding public transport, service schedules with daily and weekly variability underscores how urgent the dynamic approach is. However, schedules have not always been available, sufficiently detailed per route segment or realistic, meaning that the effect of road congestion and possible disruptions may not have been considered (Lei and Church, 2010; Moniruzzaman and

Páez, 2012). The recent development of specific data formats to process schedules in transit accessibility, like GTFS (Google Transit Feed Specification), along with bespoke analysis tools, opens up new research opportunities (Farber et al., 2014; Jäppinen et al., 2013; Lei and Church, 2010).

As for activity levels and transport demand at destinations, traditionally, accessibility studies have used census data to represent the importance of destination zones. These data show where people live, which can serve as a good proxy for representing the accessibility conditions of the evening and night periods, when people are usually at home. However, during the day, people perform several activities at different places, and other variables can be used, such as employment or the location of specific services (i.e., schools, hospitals, stations, or airports). Recently, other data sources from portable technologies or sensors installed at different locations are being used to represent the daily changing patterns of the population in accessibility studies. This is the case of mobile phone data (García-Albertos et al., 2019; Järv et al., 2018), or social networks (Moya-Gómez et al., 2017). Those studies were able to represent the increase in accessibility associated with certain activities that characterize those places. Thus, business districts increase accessibility during working hours while shopping zones show peaks of accessibility during lunch and afternoons. However, some of these data sources have been criticized as biased, only representing a segment of the population, as in the case of social networks. Access to more representative data as mobile phones, although very promising (García-Albertos et al., 2019), is often very costly. Therefore, many accessibility studies avoid considering the dynamic nature of destination attractiveness. In this paper, we contribute to the accessibility literature by incorporating the dynamism of transport networks (roads and bus networks and schedules), together with the daily variation of the population at destination zones, as a proxy for the desire of travel to certain destinations and the attractiveness of destination zones.

The Accessibility Gap

Access to activities can be facilitated by different modes of transport. However, accessibility analyses have traditionally focused on only one transport mode. The importance of measuring accessibility through different modes lies in the fact that not every citizen has equal access to the same modes due to financial, physical, locational, or lifestyle reasons. Low-income individuals heavily rely on public transport, while low-income neighborhoods typically lack adequate public transport options (Chen et al., 2021; Delmelle and Casas, 2012). On the other hand, each person has limited time to engage in certain activities, and their time budget might not be compatible with the activities' opening hours. This becomes particularly significant when traffic conditions are poor or there is no effective public transport alternative. Peripheral locations are a clear example of these areas, characterized by less frequent and less extensive public transport systems compared to central and consolidated areas.

A comparative multi-modal perspective in accessibility analysis is becoming increasingly relevant. Many comparative studies have risen in recent years,

measuring the competitiveness of public transport systems and private transport, known as the accessibility gap. All of them advocate the need to promote sustainable mobility policies and limit the use of cars. To achieve this, cities must offer good access conditions and convenient public transport frequencies so that they can be competitive and enable a modal shift from private vehicles to public transport. However, in many of the reviewed studies, a clear advantage of cars has been measured compared to other modes (Abdelwahab et al., 2021; Maharjan et al., 2022). This is due to the historical planning of our cities towards car-oriented mobility.

The accessibility gap has been approached from two main perspectives: social and transport-oriented. From a social perspective, previous literature has identified areas of transport needs and transport demand and supply mismatch. Transport needs are usually determined by examining the population at risk due to car ownership (Maharjan et al., 2022), financial constraints (Costa et al., 2021; Yan et al., 2022), or a combination of social factors (Fransen et al., 2015; Kawabata and Shen, 2007b). In these studies, the transport offer is usually assessed by measuring the accessibility levels provided by the public transit system (Giannotti et al., 2022) or by comparing the accessibility of public transport with that of private vehicles (Cui et al., 2022; Zhu and Shi, 2022). Some studies have found that areas with public transport disadvantages are associated with a higher share of carless households (Maharjan et al., 2022). In such cases, the analysis of the accessibility gap can help identify the most vulnerable locations where improving the public transport offer can have positive consequences for the most vulnerable groups of residents.

From a transport perspective, the accessibility gap has been measured by comparing the levels of service of public transport and cars and determining areas of public transport disadvantage. Those areas are prioritized for public transport improvements to increase the competitiveness of public transport services and reduce car usage (Benenson et al., 2011; Kwok and Yeh, 2004; Niedzielski & Kucharski, 2019; Salonen & Toivonen, 2013). Some authors refer to this as the modal gap (Chen et al., 2020; Kwok and Yeh, 2004) or relative accessibility (Benenson et al., 2011; Zhu and Shi, 2022) as it is based on comparisons of transport modes. In all the reviewed studies, the disadvantage of public transport is directly related to the availability of these services. Therefore, most studies observe smaller accessibility gaps, or even a relative competitive advantage of public transport in city centers (Fransen et al., 2015; Maharjan et al., 2022; Mocanu et al., 2021; Salonen & Toivonen, 2013) or near public transportation corridors or stations (Chen et al., 2020; Widener, 2017) where the accessibility to public transport services is higher.

Regarding how the accessibility gap has been measured in the literature, studies have used accessibility indicators normally based on travel times, as an important determinant of modal choice. When generalized transport cost was used, the competitive advantage of public transport was evident (Abdelwahab et al., 2021), especially for poor people (Pereira et al., 2024). The most commonly compared modes of transport are private vehicles and public transport, but there are examples of other modes, such as bicycles (Chen et al., 2020; Romanillos and Gutiérrez, 2020), or walking (Wu et al., 2021). The accessibility gap has been measured by considering the accessibility to key areas like the CBD (Costa et al., 2021), or to services such as

schools (Pizzol et al., 2021), public libraries (Salonen & Toivonen, 2013), or parks (Omer and Or, 2005).

Recent studies on the accessibility gap are characterized by greater spatial and temporal disaggregation of data and its results, due to the expansion of technologies, such as GPS, mobile phones, and sensors that accurately represent road congestion and the spatial distribution of the population. Therefore, the accessibility gap has also been analyzed considering its spatiotemporal variation, using data from applications such as Google (Barboza et al., 2021; Costa et al., 2021; Cui et al., 2022), Baidu Maps (Yang et al., 2017), and GPS tracks of vehicles (Guan et al., 2020). When measuring the accessibility of public transport, recent studies benefit from the extended availability of updated timetables, which have led to comparative studies on accessibility variations throughout the day and between days of the week (Fayyaz et al., 2017; Fransen et al., 2015; Giannotti et al., 2022). Some studies take a step further, considering the GPS data of buses that account for daily incidents in public transport (Wessel and Farber, 2019).

The improvement of data has resulted in more accurate accessibility gap analyses, for example, considering the impact of congestion on roads or the level of public transport service. Although private vehicles continue to have a clear advantage over public transport, new data have shown that the accessibility gap varies at different times of the day. These studies show that if road congestion and public transport service levels are not considered, the advantage of cars over public transport would be overvalued, especially during peak hours when access by private vehicles is impaired due to congestion. On the other hand, during rush hour, public transport tends to have more frequency, resulting in a competitive advantage for this mode of transport, if the correct infrastructure is in place (Chen et al., 2020; Maharjan et al., 2022; Mocanu et al., 2021).

Studies that analyze the accessibility gap in spatial-temporal terms (Kawabata and Shen, 2007b; Liao et al., n.d.; Yan et al., 2022) can be helpful in jointly determining the places and moments where public transport should be improved (Liao et al., 2020; Moyano et al., 2018). However, revised studies have only introduced dynamism in the transport component of accessibility indicators, considering road congestion and public transport frequencies. In this study, we intend to go one step further in the analysis of the accessibility gap, allowing the temporal variation of travel times as well as activity levels. Considering the number of people that arrive at each destination area at different times of the day will improve the measurement of accessibility temporal dynamics within a city and provide a more realistic comparison between transport modes.

Latin America and the Case of Curitiba

Decision-makers in Latin America have not typically taken accessibility analyses into account (Vasconcellos, 2019). Perhaps as a consequence, the few academic papers using accessibility metrics in Latin American cities are very recent (Bittencourt and Giannotti, 2021; Costa et al., 2021; Giannotti et al., 2021; Haddad et al., 2019; Pizzol et al., 2021; Pritchard et al., 2019; Slovic et al., 2019). Furthermore,

due to the high level of social inequality, analyzing accessibility requires special care in Latin American cities, as the consideration of transport "demand" is less homogeneous than in the Global North. Traditional approaches to accessibility may neglect social inequity and constraints suffered by the disadvantaged. For example, low-income households often rely on public transport, thus enduring longer commutes (Pereira et al., 2017; Vasconcellos, 2018). As a result, low-income groups should be the focus of mass transit investments. However, recent studies have found that middle- and high-income groups take the most advantage of new flagship transit services, like a new BRT line in Colombia (Delmelle and Casas, 2012), and the new mass-transit network in Rio (Pereira et al., 2019a, 2019b), thus reinforcing pre-existing spatial inequalities.

Curitiba's land-use transport coordination model is often signaled as a world-wide-relevant success story, resulting in "the greenest city in the world" (Moore, 1994). It is based on bus-rapid transit (BRT), which is a relatively inexpensive alternative to rail systems: buses run on segregated lanes, providing comfortable, secure-boarding stops, and payment advantages (Duarte and Ultramari, 2012; Rabinovitch, 1992). Planning documents allow dense developments like high-rise buildings only along the BRT corridors to encourage public transport demand. Additionally, to support foot access in the first/last mile, building basements along the corridors are reserved for commercial activities, which enhance pedestrian comfort, attractiveness, and natural surveillance — following Jacobs' concept of "eyes on the street" (Jacobs, 1961).

A recent paper analyzing seven middle-sized Brazilian cities found that Curitiba provided the highest accessibility to its central business district (CBD) from the urban fringe, thanks to the public transport competitiveness vis-à-vis automobiles. However, not all studies have been as positive. Recent accessibility studies in Curitiba found important inequalities in access to work, education and healthcare (Bittencourt et al., 2021; Boisjoly et al., 2020; Pereira et al., 2019a, 2019b). Some authors claim that Curitiba's land-use transport model neglected the socio-economic dimension, resulting in a socio-spatial mismatch: BRT users do not live along the BRT corridors, but in the outskirts, whereas high-income households at BRT corridors continue using their private cars (Turbay et al., 2024; Duarte and Ultramari, 2012; Ghidini, 2009). The present study will contribute to this debate by comparing the accessibility of Curitiba's public transport system and its car accessibility while identifying the places and moments of the day when the public transport offer should be improved to be competitive.

Methodology

The Methods

The choice of accessibility measure is crucial, as different measures may lead to contrary results (Niedzielski & Kucharski, 2019). Also, when comparing modal accessibility measures, it is important to maintain consistent conceptualization and level of detail in modeling (Salonen & Toivonen, 2013). To analyze

the dynamic accessibility of Curitiba (both land use and transport), the potential accessibility indicator was selected (Eq. 1). This indicator was first introduced by Hansen (Hansen, 1959), and it is one of the most used accessibility indicators in the literature, given its capacity to effectively reproduce the mobility behavior of citizens. This study uses the following formula:

$$A_{i,t,m} = \sum_{j=1}^n O_{j,t} f(C_{ij,t,m}) \quad (1)$$

Where:

$A_{i,t,m}$ is the potential accessibility of origin zone i at time t and mode m

$O_{j,t}$ is the opportunities at destination zones j at time t

$f(C_{ij,t,m})$ is a function of travel time (C) for mode m between i and j , at time t , also known as distance decay.

The outcomes directly depend on the available opportunities for interaction and will be inversely affected by the distance needed to reach them. The higher its value, the higher the accessibility of a given zone. This indicator requires the calibration of the distance decay function, which shows the diminishing effect of distance on the attractiveness of destination zones. The function can take several forms (Reggiani et al., 2011) however, it is commonly accepted that the negative exponential function better adjusts to intraurban models. This function can be estimated using observed mobility patterns, usually obtained from mobility surveys. In our case, we use the last publicly available mobility survey for the Curitiba Metropolitan Area (IPPUC, 2017). The distance decay function calibrated in this study was the negative exponential, as shown in Eq. 2:

$$f(C_{ij}) = e^{(\beta C_{ij})} \quad (2)$$

Where:

β represents the magnitude of distance decay. Higher values impose higher weights on closer relationships. We obtained a value of -0.0713 by linearly adjusting the log of trips between transport zones and the average travel times for these origin-destination relationships. For calibration purposes, we have used the total number of trips per day from an origin to a destination, including both car and bus modes.

To compare private and public transport accessibility and measure the accessibility gap, the following ratio is used (Eq. 3):

$$AG_{i,t} = A_{i,t}(\text{private vehicle}) / A_{i,t}(\text{public transport}) \quad (3)$$

The accessibility gap (AG) is a ratio between private and public accessibility levels at zone i at time t , showing how similar they are in relative terms. Values close to 1 indicate equal levels of accessibility for both modes; higher values represent an advantage of car over bus accessibility, while values lower than 1 represent the opposite situation.

The Data

Travel times are calculated at the transport zone (TAZ) level and are estimated from two different data sources. TomTom API Traffic Stats® was used to represent the traffic conditions by car. It includes a detailed road network containing traffic average speeds for 24 hours gathered every hour. For public transport, Google Transit Feeds (GTFS) was used, containing the frequencies and travel times of Curitiba’s bus network (Fig. 1). This source belongs to Curitiba’s local transport authority. The bus network is combined with a pedestrian network from OpenStreetMap to ensure connectivity between bus stations and door-to-door calculation of travel times. This network was checked and corrected for topological errors to ensure accuracy.

The car and bus networks are referenced to 2017 and are limited to the municipality of Curitiba, given the lack of GTFS data for the entire metropolitan area. For GTFS, a typical weekday (Tuesday) was selected to compute travel times. For the road network, TomTom data provides average hourly speed profiles, considering only working days in 2017. The analyzed time period ranges between 5 a.m. and 11 p.m. when bus services are fully operating.

The opportunities (O_j , at eq. 1) representing the attractiveness of destination zones are proxied by the number of trips reaching each destination at each hour (Fig. 2) according to Curitiba’s Mobility Survey (IPPUC, 2017). The number of

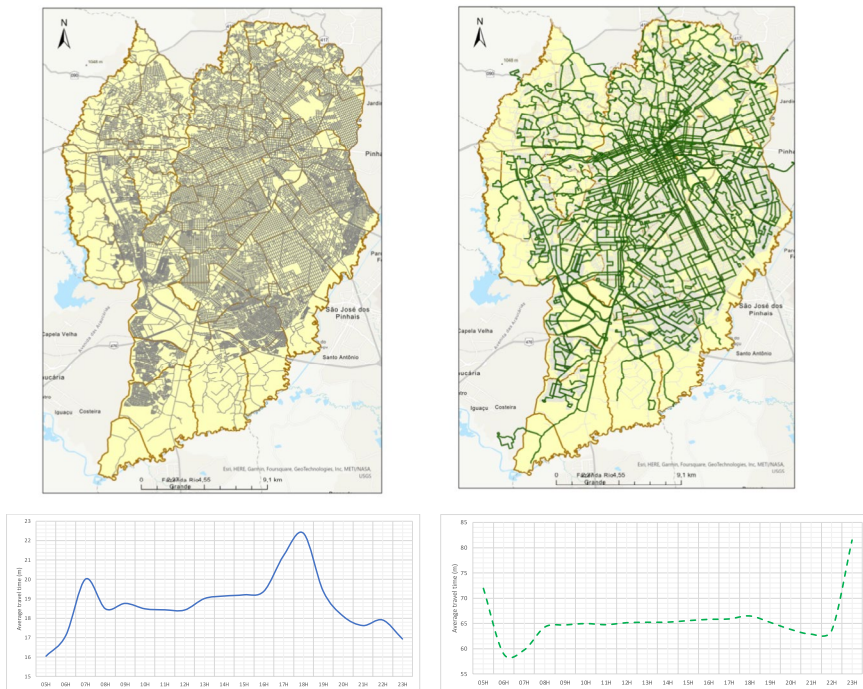


Fig. 1 Road and bus networks (top left and top right, respectively) and average travel time between TAZ for car and bus modes (bottom left and bottom right, respectively) (Source: the authors)

trips between zones is expanded to the entire population of Curitiba. Trips are aggregated hourly (without differentiation by days of the week), considering all transport modes and all trip purposes to avoid having an origin-destination matrix with many zeros. Thus, we take the number of trips a location receives as a proxy of its activity levels, assuming the more active a zone is, the more attractive it becomes, following a similar approach as some of the studies presented in section "Dynamic Accessibility and new data sources".

With the previous data, we can estimate the accessibility of Curitiba per hour and compare daily accessibility variations considering car and bus modes. Variations will arise due to road traffic conditions in the case of the car mode and bus frequencies for the bus mode. The daily variation of destination attractiveness (trips reaching each destination zone) is expected to impact accessibility levels depending on the land use specialization of each location. Business centers will probably be more attractive during working hours, while residential areas will increase their attractiveness in the afternoons when people return to their homes.

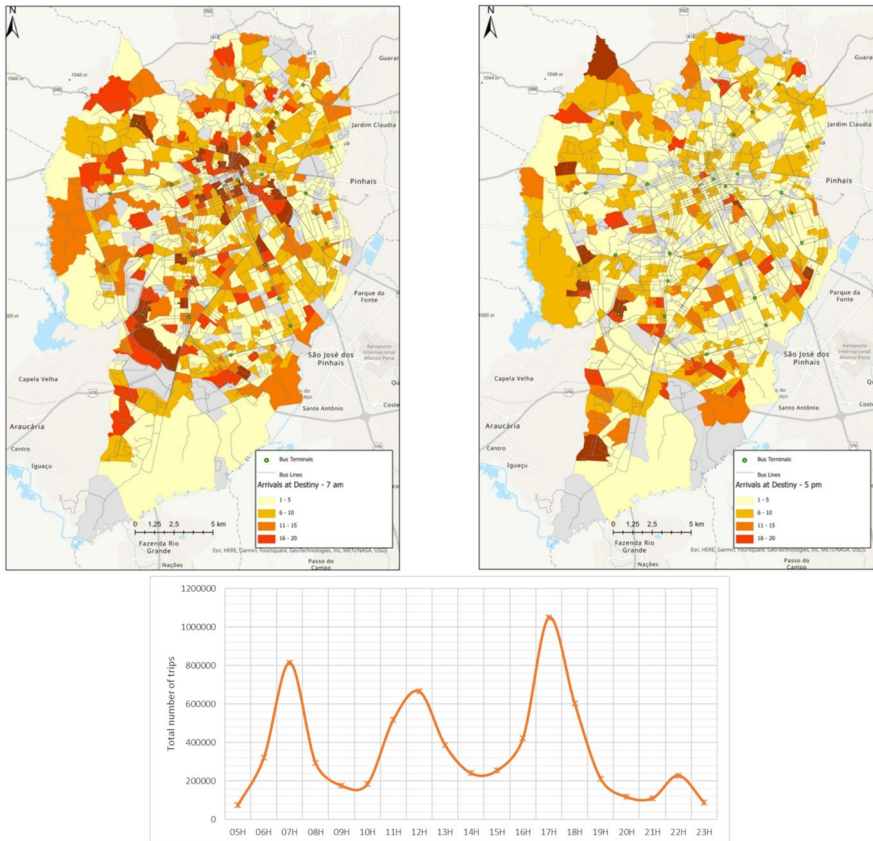


Fig. 2 Number of trips reaching a destination at 7 am and 5 pm (top left and top right, respectively) and daily variation of total trips reaching TAZ (bottom graph) (Source: the authors)

Outcomes

Spatial and Temporal Variation of Curitiba's Accessibility

In this study, we measure accessibility considering the dynamism of road congestion and bus frequencies, together with the number of trips reaching a destination at specific hours. Regarding accessibility by car (Fig. 3), we can identify three prominent accessibility level peaks. The first one occurs between 7 a.m. and 8 a.m. when more trips to work and study places occur, increasing the attractiveness of specific destinations and, therefore, accessibility levels. The second one happens around noon, coinciding with lunchtime. The most important peak occurs when the regular workday ends, between 5 p.m. and 6 p.m., when a high number of trips are reported in the mobility survey, increasing the accessibility of desired destination zones. Finally, a much smaller peak is registered around 10 p.m. when shopping activities close, and people return to their homes.

Comparing Fig. 3 with the graphs of Fig. 1 (left side) and 2, we can conclude that the daily variation of potential accessibility depends highly on daily trip patterns, as both curves present a similar shape. Travel times by car also show the morning and afternoon peaks, with the afternoon peak occurring between 6 and 7 p.m., but congestion levels operate in the opposite direction, lowering the accessibility in the study area.

Figure 4 shows the spatial distribution of accessibility by car in Curitiba. Higher levels of accessibility (darker colors) happen at the three peak hours mentioned before (at 7 a.m., 12 p.m., and 5 p.m.). As we have seen in the previous figure, accessibility variations are highly influenced by the daily patterns of trips, while the attractiveness of destinations is affected by their land-use mix. At 7 a.m., accessibility levels increase in the central city, where most jobs and educational institutions are based. This tendency is also the case in other zones, such as the Curitiba industrial

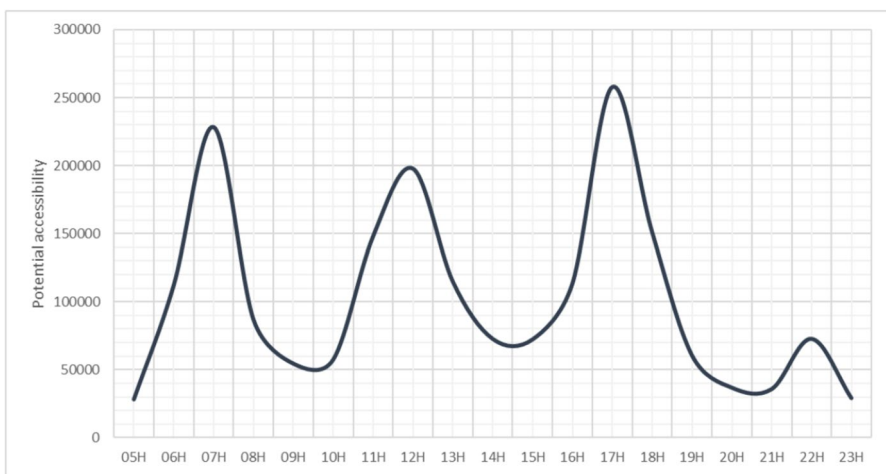


Fig. 3 Daily accessibility pattern of private vehicles (Source: the authors)

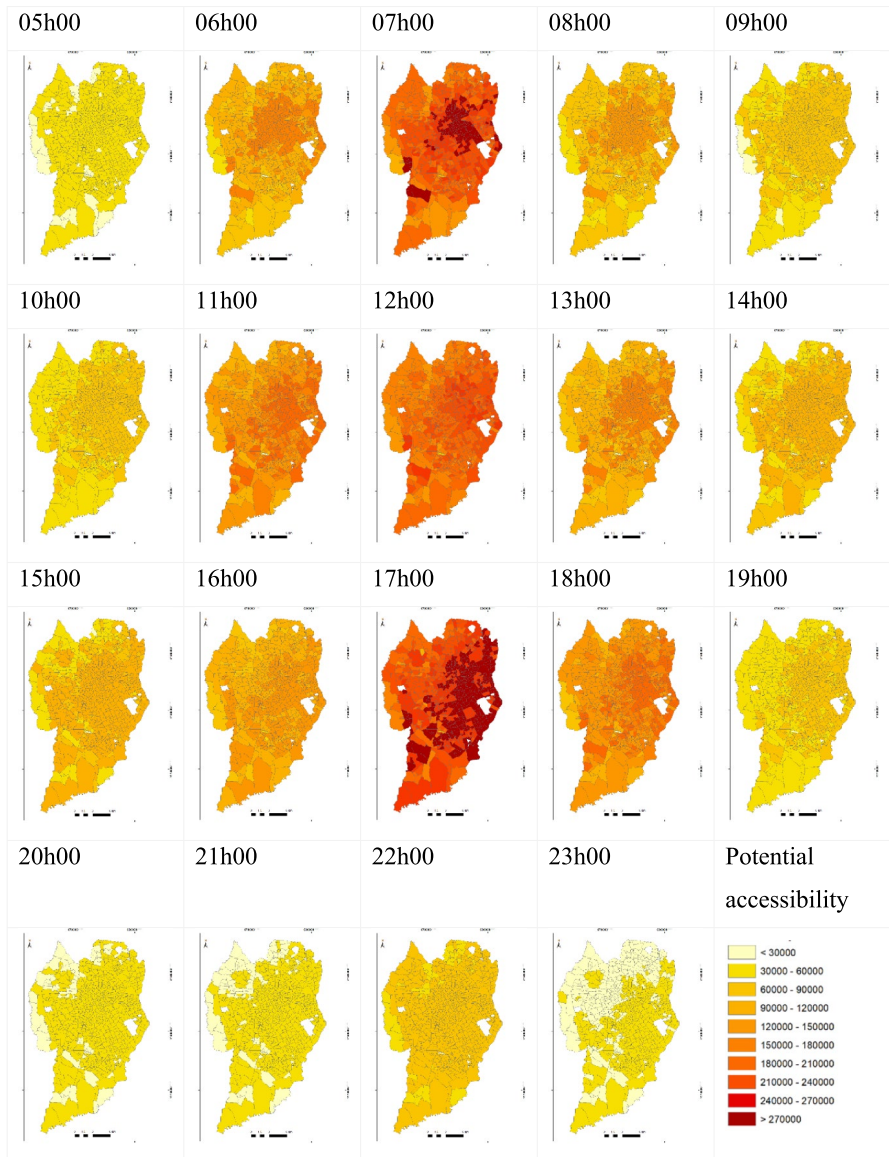


Fig. 4 Potential accessibility by car at TAZ level (Source: the authors)

zone, located in the southwest of the municipality. The second accessibility peak, at noon, shows a more scattered pattern, with accessibility levels increasing more evenly throughout the city. Finally, in the third peak at 5 p.m., zones with higher accessibility are mainly residential and commercial zones, coinciding with the end of the workday and the arrival at shopping and home places for many people.

As for accessibility by public transport, a similar daily pattern can be deduced, with three prominent peaks at 7 a.m., 12 p.m., and 5 p.m. (Fig. 5), coinciding with the periods with higher transport demand. However, for public transport accessibility, much smaller accessibility values are registered due to the increase in travel times associated with this transport mode, which imposes a higher discount on the opportunities available for interaction. The average travel times remain stable for around 60 minutes (compared with the 20-minute average travel time of cars), only decreasing between 6 a.m. and 7 a.m. and after 6 p.m. due to increased bus frequencies (Fig. 1, bottom right).

Figure 6 shows the distribution of accessibility levels in space and time. In the case of bus accessibility, we can observe a more concentrated pattern of high values around the central area of Curitiba. This spatial pattern is undoubtedly influenced by the type of zones and their capacity to attract more trips at specific hours, as mentioned before, but it is also due to a higher concentration of bus services in the central city. The bus network reinforces accessibility disparities, benefiting the central zones and areas close to bus lines and stops. On the other hand, peripheral locations are characterized as being less attractive (receiving a lower number of trips) and having a less dense bus network and frequencies, which explains the lower levels of accessibility.

Curitiba's Accessibility Gap

The accessibility gap illustrates the relative disparity between car and public transport accessibility. As elucidated in section "Methodology", values above 1 indicate greater accessibility by car and a less efficient bus service. In the preceding section, we observed that accessibility by car consistently surpasses that by bus, but some variations can be discerned (Fig. 7). For instance, at 5 a.m., when there is minimal bus service and congestion levels are low, the car exhibits a significant advantage over bus accessibility. A similar scenario unfolds outside peak hours

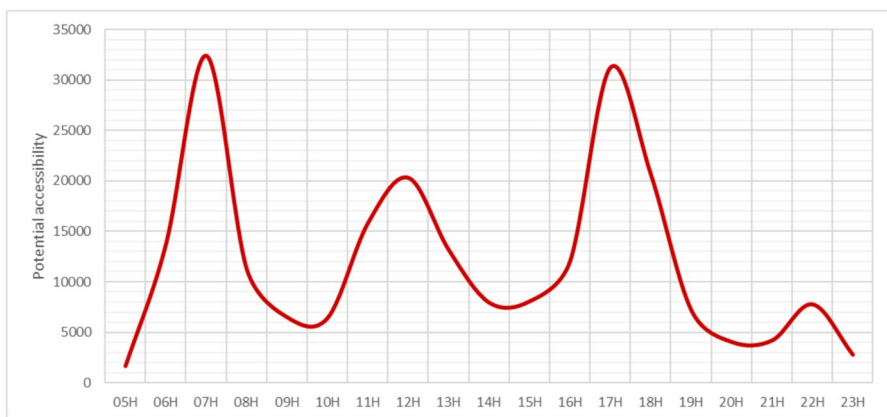


Fig. 5 Daily accessibility pattern of bus transport (Source: the authors)

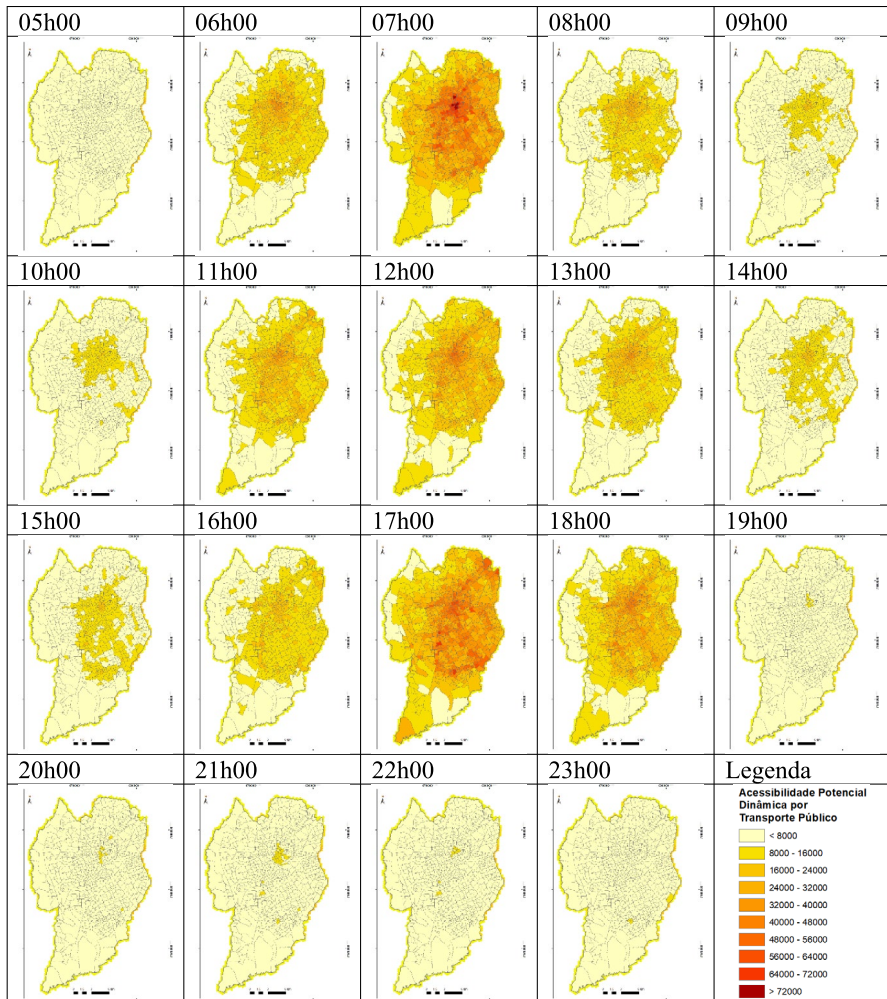


Fig. 6 Potential accessibility by bus (Source: the authors)

when congestion levels decline, amplifying the competitive edge of cars. During the morning and afternoon rush hours, and to a lesser extent at noon, the disparities between the two modes diminish. This outcome arises from the combined impact of two factors: firstly, heightened congestion levels curtail car accessibility, whereas buses, theoretically unaffected as we operate with timetable data that does not consider congestion, maintain their service levels; secondly, the increased frequency of buses during peak hours reduces waiting times, enhancing travel times and accessibility levels for this mode of transport.

Some periods during the day present high disparities in the accessibility gap, indicating that certain zones have very poor levels of public transport service (Fig. 8). This occurs mainly between 11 a.m. and 12 p.m. and at 2 p.m., 3 p.m., and 10 p.m.

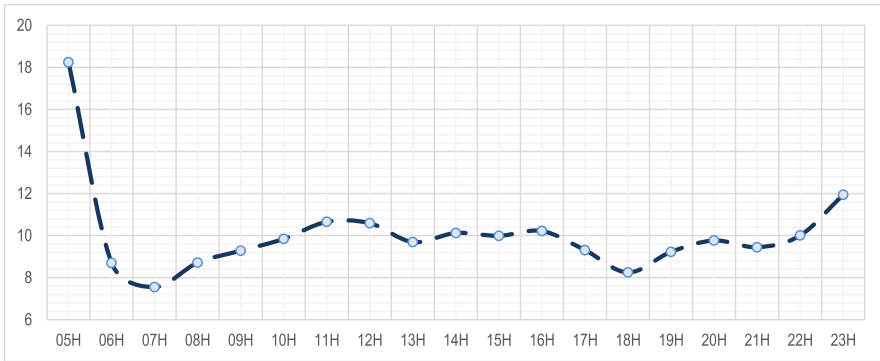


Fig. 7 Daily variation of accessibility gap (median values) (Source: the authors)

The spatial distribution of the accessibility gap (Fig. 9) reveals the most significant relative differences in the periphery, while central areas enjoy relatively similar levels of accessibility in both modes. This trend persists throughout the day in general terms. When we correlate this outcome with the previous section, it suggests that central areas have good accessibility levels considering both bus and car modes, while peripheral areas have comparatively lower levels of bus services.

During rush hours, the accessibility gap narrows from the center to the periphery, especially towards the neighborhoods located on the east side of the city, where a good portion of the lower and middle-class inhabitants reside. In these areas, the competitiveness of the bus system increases. The highest accessibility gaps are found in areas located in the west and southeast of the city, due to inadequate bus infrastructure. However, in the western part, this gap might have fewer negative impacts since these areas host middle and upper-class incomes, which are mainly car-dependent and have more transport options than deprived locations.

Once we have observed the temporal and spatial variation of the accessibility gap in Curitiba, we aimed to analyze the social impact of the accessibility gap on the resident population. To accomplish this, we classified TAZ according to accessibility gap quintiles for each hour and counted the total population (Fig. 10). In general

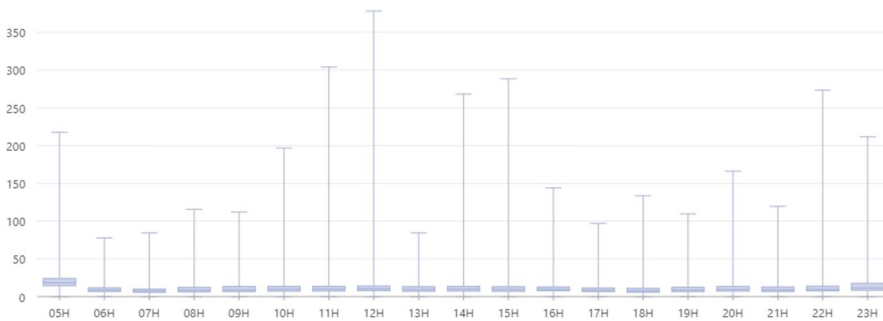


Fig. 8 Daily variation of accessibility gap (median values) (Source: the authors)

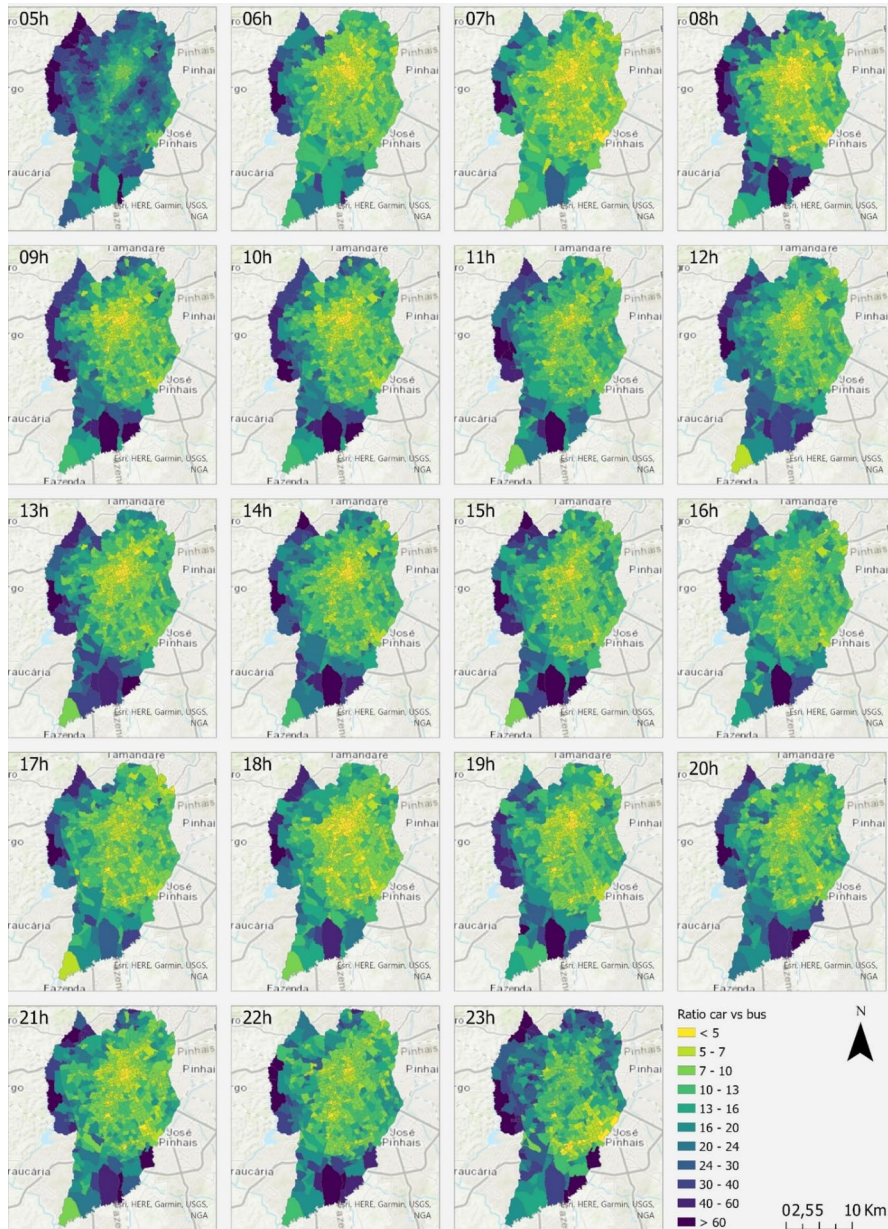


Fig. 9 Spatial and temporal distribution of the accessibility gap (Source: the authors)

terms, the results show that only a small portion of Curitiba's population (less than 15%) experiences low levels of the accessibility gap. The majority of the population faces a deficient bus service, making it challenging to shift to the bus mode and hindering a transition towards more sustainable mobility.

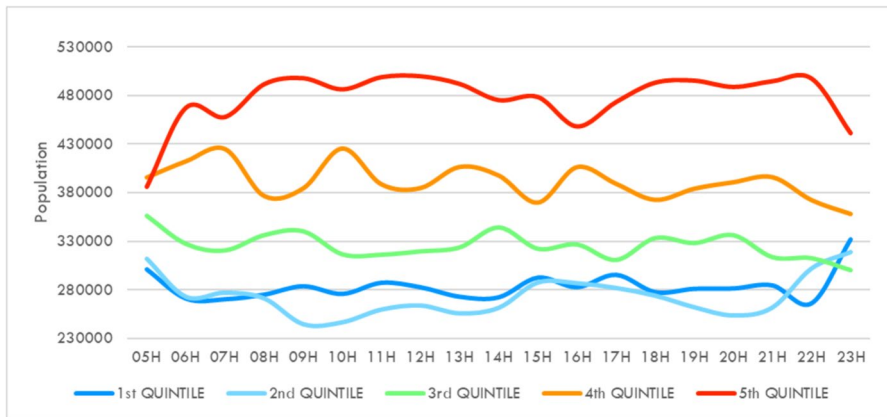


Fig. 10 Population distribution across accessibility gap levels (Source: the authors)

Discussion and Conclusions

This study analyzes the accessibility gap in the city of Curitiba, which is a paradigmatic example of Bus Rapid Transit development in Latin American cities. By comparing two modes of transport—cars and buses—and utilizing big data-informed sources, we were able to measure the temporal and spatial variations of accessibility within the city. One of the main innovations of this paper is to consider the dynamic nature of accessibility when measuring the accessibility gap, incorporating the changing conditions of transport networks caused by congestion and bus frequencies, along with the hourly number of trips arriving at each destination area, as a proxy of the activity level and attractiveness of each location. This temporal component, often ignored in transit accessibility modeling (Malekzadeh and Chung, 2020), provides a more realistic perspective on the accessibility disparities between car and public transport.

The results demonstrate the fluctuation in accessibility conditions throughout the day and the influence of factors mentioned above—congestion levels, bus frequencies, and the number of trips reaching an area. In the case of Curitiba, we observe that the daily variations in accessibility follow the spatial and temporal patterns of trips within the city, which, in turn, are related to the land use specialization of transport zones. During the morning, accessibility for both car and bus modes increases in the city center and zones with high employment levels, while in the afternoon, residential zones experience enhanced accessibility as many people return to their homes.

The main finding of this research is the significant accessibility gap between private vehicles and public transport in Curitiba, with a higher competitive advantage for car accessibility, despite Curitiba's investment in BRT services. However, the results demonstrate temporal and spatial differences alongside this general trend. The accessibility gap is lower during rush hours when car congestion levels are higher, and bus frequencies improve bus competitiveness. Furthermore, the accessibility gap is generally lower around the city center and bus corridors, where the availability of bus services is higher, both in terms of bus stops and service frequencies. The higher flexibility and speed

of cars make them particularly advantageous in areas with dispersed land-use patterns, where destinations are spread out and public transport networks are less dense.

Additionally, our results indicate that the accessibility gap is not evenly distributed across the population. More than half of Curitiba's population faces high levels of accessibility gap due to a deficient public transport offer. Our findings are consistent with previous studies on BRT services in Latin America (Venter et al., 2018), which show that benefits are often skewed towards a small part of the population due to insufficient spatial coverage and inappropriate fare policies.

Curitiba faces a significant challenge in achieving equitable and sustainable transport accessibility. Despite investments in public transport infrastructure, particularly its renowned BRT system, accessibility gaps between private vehicles and buses remain substantial, especially in peripheral areas. These disparities are not uniform; they vary spatially and temporally, narrowing during peak hours when bus frequencies increase and road congestion affects car travel. However, more than half of the population still lacks adequate public transport access, making it difficult to shift toward sustainable mobility options. Addressing these gaps will require targeted interventions to improve bus service coverage and frequency, particularly in underserved areas. Such efforts are essential to reduce reliance on private cars, foster social equity, and promote environmentally sustainable urban development.

This work provided a framework to diagnose the competitiveness of buses over cars and for evaluating the impact of interventions like the introduction of Bus Rapid Transit (BRT) systems or traffic demand management policies. By measuring the accessibility gap, we can identify the periods and locations where public transport should be improved. If the gap between accessibility levels provided by public transport and cars is significant, then a sustainable change of habits may require sacrifices that many may not be willing to make. As for urban planning, integrating this accessibility framework into urban development plans can guide zoning decisions, ensuring high-density developments are concentrated in areas with good public transport accessibility and low accessibility gap. This methodology is particularly relevant for cities in the Global South experiencing rapid population growth and transport challenges. Cities with emerging BRT systems or those planning public transport expansions could benefit from adopting this framework. Furthermore, the methodological framework can be implemented across multiple cities to benchmark accessibility levels and identify best practices that could be transferred to other contexts.

Despite methodological advances, the conclusions must account for certain limitations. First, The reliance on GTFS and TomTom Traffic Stats data provides sources describe normal conditions only, and cannot be used to consider extraordinary, unexpected disruptions caused by, for instance, extreme weather events. However, novel big data sources can be used to evaluate the level of disruption caused by this kind of events (Santiago-Iglesias et al., 2023). Further, the analysis focuses on a single representative day (Tuesday), overlooking normal variations during weekends or holidays.

Second, the model assumes static travel demand based on a single mobility survey, which may not reflect changes in socioeconomic dynamics or urban development. The distance decay function calibration, while suitable for general urban patterns, may not capture differences among social groups or geographic areas. By

excluding alternative modes of transport like cycling or walking and limiting the scope to Curitiba's municipality, the analysis lacks broader regional mobility patterns. Although the hourly resolution captures dynamic trends, finer granularity during peak periods could enhance accuracy and applicability.

Future research lines include analyzing socio-economic disparities in the accessibility gap, which could identify not only the number of people living in areas with higher accessibility gaps but also characterize the socio-economic conditions of those individuals. These outcomes could be used to identify market opportunities and transport solutions tailored to each socioeconomic group residing in specific locations. In terms of data, the present analysis could be expanded if GTFS data for the Curitiba metropolitan area were available. Furthermore, incorporating bus GPS tracks could enhance GTFS data, as relying solely on scheduled data might overestimate public transport accessibility.

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Data Availability The data that support the findings of this study are available from TomTom Api Traffic Stats ®, but restrictions apply to the availability of these data, which were used under licence for the current study and so are not publicly available. The data are, however, available from the authors upon reasonable request and with the permission of TomTom Latin America.

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