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The equity implications of TOD in Curitiba

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ABSTRACT

Transit Oriented Development (TOD) projects are being increasingly adopted worldwide as a way to promote the coordination between transport and land-use planning. However, little attention has been given to how TOD projects are associated with socioeconomic and spatial inequalities and its effects on people's access to economic activities and public services, particularly in the Global South. In this paper we analyze how socio-spatial inequalities have been shaped by transport and land-use planning in Curitiba (Brazil), a city internationally recognized for its TOD planning based on Bus Rapid Transit (BRT). We examine how the spatial organization of the BRT system is associated with the distribution of population densities, socioeconomic groups, and real-estate values and its implications in terms of inequalities of access to employment opportunities and health services. The results show that Curitiba's TOD has had limited influence on population densities, but contributed for the unequal distribution of its benefits, privileging high-income classes and premium real-estate along its main BRT corridors. These effects contribute to push low-income communities to peripheral urban areas with limited accessibility benefits from the transit system. Our findings suggest that Curitiba's success story should be seen as a cautionary tale about the consequences of TOD planning, which perpetuate the spatial concentration of resources and reinforce inequalities of access to opportunities. The broader lesson of this study is that TOD planning must be constantly evaluated by its socials and environmental impacts, and be guided by mixed housing, and social inclusion to avoid potential consequences in terms of segregation and peripheralization of poorer communities.

1. Introduction

Curitiba is known worldwide for what is today considered one of the first comprehensive implementations of a Transit Oriented Development (TOD) Master Plan (Duarte et al., 2011; Lindau et al., 2010). Curitiba's TOD was planned in the 1960s as a comprehensive urban policy built around transit corridors which were used to organize and induce linear urban expansion according to strict land-use regulations (Oba, 2004; Mercier et al., 2015). The system enabled by a Bus Rapid Transit (BRT) network was considered innovative by urban and transport planners across the world (Cervero, 1998; ICLEI, 2016; Khayesi and Amekudzi, 2011), and it is still the basis for the city's international reputation as a reference for urban planning (Nakamura et al., 2017; de Freitas Miranda and da Silva, 2012; PMI, 2019).

Nevertheless, despite the widespread acclaim for the tight integration of transportation and land-use planning, inquiries into the underpinnings and repercussions of Curitiba's urban policies have held the interest of scholars for many years. This interest intensified, particularly in the 1990s, as certain adverse consequences of Curitiba's renowned urban planning approach began to manifest.

This critique revolves around the prioritization of urban planning as a commodity aimed at crafting a city's image, often obscuring the genuine intricacies and local identities (Garcia, 1997). It also delves into the tendency for affluent segments of the population to dominate the occupation of areas abundant in opportunities and resources (Pilotto, 2010), particularly along TOD corridors for high-end real estate ventures (Fernandes and Firkowski, 2014). Duarte and Ultramari (2012) extend this literature byinghow the benefits of TOD policies in Curitiba are distributed spatially and across socioeconomic groups. The focus is the critical understanding of the equity implications of Curitiba's TOD in terms of its role in contributing to shape socio-spatial inequalities in the distribution of land values, socioeconomic classes, and transport inequalities.

This paper examines the association between Curitiba's TOD strategy

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and socioeconomic and transport inequalities. We analyze how the organization of the BRT network relates to uneven spatial distribution both of population densities, land values and of social classes, and how it contributes to shape the extent to which different income groups benefit from Curitiba's BRT in terms of transit accessibility. Using detailed estimates of transit accessibility to employment opportunities and healthcare services, we show how the accessibility benefits of TOD have disproportionately favored high-income groups, reflecting important inequitable outcomes from TOD models in the long term. Using detailed cross-sectional data on land values at parcel level, and spatial distribution of socioeconomic groups, employment opportunities and healthcare services, we examine the relationship between the city's TOD strategy and land values along Curitiba's BRT main axes and its spatial implications for unequal access to opportunities and socio-spatial segregation.

The remainder of this paper is organized as follows. Section two presents a review of the literature on the concepts of TOD and its relationship with accessibility and transportation equity. Section three presents the historical context of Curitiba's TOD implementation and its BRT network. Section four describes the data and methods used in this study. In section five we present our findings on the spatial association between the BRT network and distribution of population densities, socioeconomic groups, real-estate values and transit accessibility. Finally, in section six we discuss some of the main findings of this study and reflect on what broader lessons about TOD and inclusive planning can be drawn from Curitiba and applied to other contexts.

2. TOD, urban accessibility and equity

Transit-Oriented Development (TOD) has been proposed by several authors as an effective alternative for the promotion of urban sustainability (Calthorpe, 1994; Cervero, 1998; Cervero and Sullivan, 2011; Qviström and Bengtsson, 2015; Loo and du Verle, 2017). The integration between transport and land use policies is seen as key ingredient for promoting accessibility, active mobility, and public transport (Banister, 2011; Cervero, 2014).

The concept Transit-oriented Development (TOD) emerged in the context of the New Urbanism movement in the USA in the late 20th century, in a publication on the ecology of communities (Jamme et al., 2019; Carlton, 2009). The essential idea of TOD is for compact urban development to be driven by mixed land use along mass-transit corridors that promotes proximity between housing, services, economic activities, and amenities, contributing to higher accessibility levels and social equity (Calthorpe, 1994; Dittmar and Poticha, 2004).

Some of the main benefits of TOD discussed in the literature would be to reduce the dependency on motor vehicles, achieved through a combination of mixed communities and proximity between people, activities and transport services (Bernick and Cervero, 1997; Dittmar and Poticha, 2004, Carlton, 2009). Provision of public transport, walkable infrastructure and proximity between residential and commercial use are factors that can lead to reduced car use and higher levels of transit accessibility to opportunities (Boschmann and Brady, 2013; Taki et al., 2017; Cervero and Dai, 2014; Perk and Catala, 2009).

Because of these benefits, several studies argue that TOD strategies can foster more inclusive cities and equitable transit systems with lower car dependency and greater access to opportunities for all communities (Calthorpe, 1994; Chava et al., 2018; Jamme et al., 2019; Appleyard et al., 2019; Lyu et al., 2020). On the other hand, some studies suggest that the implementation of TODs often have negative in terms of increasing land prices and segregation of social classes along TOD corridors (Padeiro et al., 2019; Chava et al., 2018), and pushing low-income communities to urban peripheral areas (Saunders and Smith, 2014; Jamme et al., 2019).

Traditionally, the discussions around TOD often focus on improving walking accessibility to transit as a way to increase transit ridership, tackle traffic congestion, and create socially cohesive urban neighborhoods (Deboosere et al., 2018). Nonetheless, the principles of TOD also embed the notion that TOD corridors play a key role in articulating both (a) the spatial distribution of land use activities, and (b) the overall organization and connectivity of the transport system. As such, it is reasonable to expect that TOD corridors have broader impacts on people's access to opportunities throughout the city, and not only nearby TOD stops. As such, there has been a growing interest in how TOD can promote equal access to opportunities (Papa and Bertolini, 2015; Renne et al., 2016; Lyu et al., 2020) and on what social equity implications it could have (Venter et al., 2018; Jamme et al., 2019). There is a growing consensus that accessibility is one of the main benefits catered by public transport systems (van Wee, 2016; Handy, 2020; Levine, 2020). Accessibility is defined as the ease with which people can reach opportunities for interaction with economic activities, public services, leisure activities, etc. (Van Wee and Geurs, 2011; Geurs et al., 2015).

A person's or neighborhood's levels of accessibility are fundamentally shaped by the integration between transport and land use systems, which can make it easier or harder for individuals and social groups to reach activities and destinations (Van Wee and Geurs, 2011; Geurs et al., 2015; van Wee, 2016; Xu et al., 2018). Particularly since the 2000s, the concept and methods of accessibility have been increasingly used to articulate the integration between urban and transport planning and its implications to social equity, economic development, and environmental impact (Feitelson, 2002; Mattioli, 2016; Boisjoly and Geneidy, 2017; Levinson and King, 2020).

The promotion of equity in transport planning is largely centered around the organization of urban environments and transit systems that increase access to economic activities, services, and amenities, particularly for vulnerable communities (Lucas et al., 2016; Pereira and Karner, 2021). Transport accessibility plays a key role as a mediator for individuals to satisfy their basic needs, to participate in social and economic life and as a determining factor of personal freedom (van Wee and Geurs, 2011; Martens, 2016; Pereira et al., 2017a; Allen and Farber, 2020). As some authors have argued, accessibility is an essential component for of social justice and social inclusion that constitute the right to the city (Fol and Gallez, 2014; Pereira et al., 2017a; Verlinghieri and Schwanen, 2020). As such, TOD, as a land use and mass transit mixing policy, can importantly contribute to reducing inequalities in access to opportunities, a key egalitarian concern in the transportation equity literature (Pereira et al., 2017b; Lucas et al., 2016).

In summary, there is a tension in the literature about the potential implications of TOD for the promotion of inclusive cities. On the one hand, the conceptual proposal of TODs is geared towards the promotion of mixed and inclusive neighborhoods that promotes urban accessibility by active and public transport modes. On the other hand, some previous experiences suggest that the uneven spatial impacts of TOD projects seem to shape real-estate markets in ways that push low-income populations away from the accessibility benefits of TOD. Next, we see how this tension has played out in Curitiba, one of 1st large-scale TOD plans in the world.

3. Curitiba's TOD

Curitiba is a city of two million inhabitants in the south of Brazil. It is the hub city of a Metropolitan region with 29 municipalities and an estimated population of 3.7 million. The city is recognized worldwide for its pioneer experience with TOD urban planning, especially for its green spaces and transport system (Rabinovitch and Leitman, 1996; Macedo, 2004). This recognition is due to a confluence of factors (Ardila-Gómez, 2004; Stewart, 2014), including the master plans of the 1940s and 1960s, known as the Plano Agache, and the Plano Preliminar de Urbanismo, respectively. This latter led to urban planning structured according to a linear development in line with TOD principles (Oba, 2004; Duarte et al., 2011; Mercier et al., 2015).

Curitiba's urban development is guided by its mains transport

corridors, known as 'structural axes', that combine high density, mass transport corridors with adjacent roads. These corridors are served by a road-based BRTs running on exclusive lanes as a central axis, with two parallel roads for the traffic of cars and other private transport modes. This combination is known as the trinary system in Curitiba's city plans (Fig. 1). In this paper we do not discuss the road system, but instead focus on public transport elements of the TOD implemented in Curitiba, which has led to its recognition as the birthplace of the BRT (Lindau et al., 2010), and culminated in the current full BRT[1] system (Duarte and Rojas, 2012). In practice, Curitiba was planned around TOD model based on BRT as transport technology (Cervero, 1998; Cervero, 2014; Suzuki et al., 2013; Hidalgo et al., 2019).

It is nearly fifty years since the implementation of Curitiba's TOD strategy and BRT system. Over the decades, the TOD and BRT have affected socio-spatial distribution and the forms of the population's mobility. Despite the expansion of the BRT network in Curitiba, the city has been witnessing constant decline in the number of users of public transport in recent years, from 1.6 M in 2015 to 1.3 M in 2019 (URBS, 2021; Duarte et al., 2011). Of the 1,3M public-transport users in 2019, 721 thousand (approximately 55 %) used the BRT system (URBS, 2022).

According to the latest household travel survey of Curitiba (IPPUC, 2017), 25,2% of all daily trips in the city were made by transit. This share is significantly lower for medium (15,9%) and high-income (7,7%) families. According to these data, the use of private motorized vehicles in Curitiba is much higher among high-income classes, who generally live (see section 5.2), closer to the main TOD axes, and served by the wide lanes dedicated to individual vehicles. By contrast, the most frequent users of public transportation in Curitiba do not live near the BRT corridors (IPPUC, 2017; Duarte and Ultramari, 2012).

Recent studies focused on transport accessibility in Curitiba have found pronounced socio-spatial inequalities in access to work, education, and healthcare (Pereira et al., 2019; Bittencourt et al., 2020; Boisjoly et al., 2020). The city that is recognized worldwide for the implementation of BRT and TOD corridors seems to present a scenario of mobility and accessibility characterized by inequality. The question that arises, and which will be explored in section 5, concerns how much Curitiba's planning favors or reinforces unequal socio-spatial distribution.

3.1. Origins and spatialization of Curitiba's TOD and BRT

The decision to adopt Transit-Oriented Development (TOD) in Curitiba was made during the 1960s, a period marked by high-density central areas and haphazard, sprawling radial expansion (Curitiba, 1965; Polucha, 2009). This transformation was initially outlined in the *Plano Preliminar de Urbanismo*, conceived in 1964 and codified into law within the 1966 Masterplan. This innovative plan reshaped Curitiba's land use and urbanization, introducing two linear axes of densification that established new zones for development, with the city's population hovering around 500 thousand (IBGE, 2010).

The 1966 plan delineated high-density zones, designed for mixed-use purposes, and laid out the linear layout of primary public transport corridors, alongside a network of high-speed avenues. This association between express bus lanes (BRT), high-density urbanization, and the promotion of mixed-use development along these structural axes characterizes Curitiba's TOD approach. It adheres to a pyramidal typology that defines decreasing construction limits as one moves away from the bus corridor toward parallel streets (Fig. 1). Local regulations specify a buffer zone of approximately 500 m with higher densities along TOD corridors.

Curitiba's BRT corridors can essentially be classified into three types based on their different characteristics with regards to land-use and occupation guidelines. The first type is defined by the structural axes, the official term in Curitiba's current urban legislation to define the transport corridors served by express BRT services. This type is characterized by TOD attributes, as high density with construction limits of four times the lot area and promotion of mixed use with commercial ground floors, covered galleries for pedestrian circulation, and the topmost floors dedicated to residential use. This type of BRT corridor, the North-South and East-West axes (Type 01 in Fig. 2), was presented in the original 1966 Masterplan ().

The second type of BRT corridor is focused on service zones and is called by local legislation as "Special Axes", with construction limit of one and a half times the lot size for services and single lot size for residential use. Unlike the first type of BRT corridor, this occupation model does not allow different land uses on the same lot, but determines urban zones specifically given over to services and residential use separated by the BRT corridors. This use and occupation model applies to the Boqueirão axis implemented in the late 1970s and the Circular Sul completed in 1999 (Type 02 in Fig. 2).

The third and final type of Curitiba's BRT corridors features construction limits of twice lot size for residential use and single lot size for commercial use, which indicates planning for mixed use with a priority for housing. This type of land-use regulation applies to the Linha Verde corridor, a new BRT axis whose construction started in 2004 and is still under construction. The purpose of Linha Verde is to transform a former federal highway with primarily industrial and service use into a mixed-use, medium-density urban area with an emphasis on mixed-use (Type 03 – Fig. 2).

In sum, the TOD Curitiba is represented by one of three types of BRT corridors with widely different characteristics in terms of land use and construction limits. The corridor known as structural axis (type 01) is the closest to a full implementation of a TOD, with integrated high density and mixed use. The other BRT corridors (types 02 and 03) are distinguished, almost solely, by the presence of the mass transit infrastructure, with no zoning patterns oriented to high density.

Regarding the construction limits, currently zoning ordinances establish the highest densities along the Type 01 corridors, the main axis of the TOD, with the construction limits of four times the plot area, and the possibility to buy two times more air rights, reaching up to six times the plot area (see Table 1). Curitiba's legislation remains faithful to the *Plano Preliminar de Urbanismo*, launched in the 1960's, to guide the much higher densities to the TOD corridors. Along Types 02 and 03 BRT corridors, the construction limit is one time the plot area, which is the most common in Curitiba's land-use legislation.

4. Data and methods

In this paper we analyze how Curitiba's BRT corridors are associated with the spatial distribution of population densities and socioeconomic groups, together with the distribution of real-estate values and inequalities in transit access to employment and health services.

4.1. Data

High resolution land-value data for 2019 come from the Real Estate Registry and Curitiba's local government map of property values.[2] The data set provides parcel-level information on land values used by the local government for urban planning and tax management purposes. Although this data set does not follow market values in real time, it does provide a good picture of how real-estate values vary across the city and real-estate units.

[1] "The main characteristics of Curitiba's BRT…include bus platforms at the same level as the floor of the bus; speedy boarding and alighting; prepaid fares; automated fare collection; greater spacing between bus stops (from 500 m up to 3 km); and integration of trunk and feeder lines in main stations: (DUARTE & ROJAS, 2012, p. 3).

[2] Available at https://geoapp.ippuc.org.br/plantagenericadevalores/.

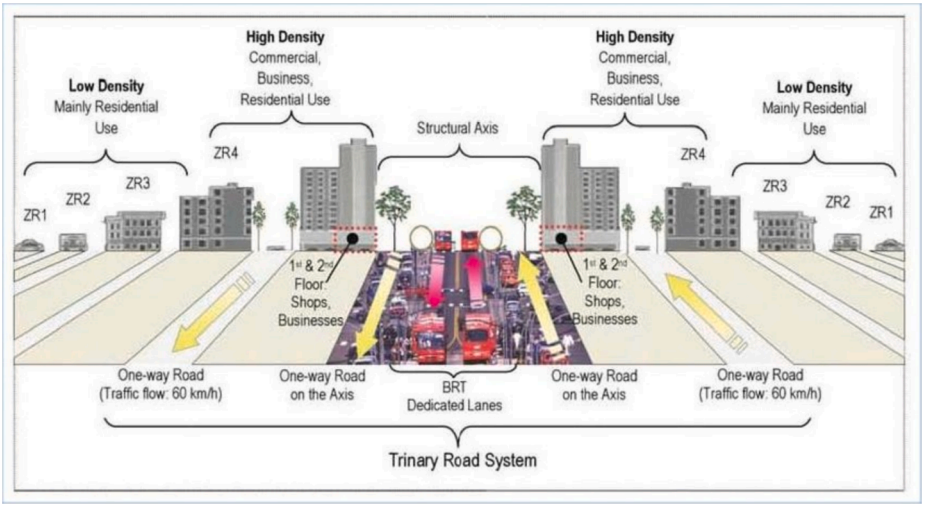

Fig. 1. Schematic drawings of the trinary system of Curitiba.).
Source: (Suzuki et al., 2013

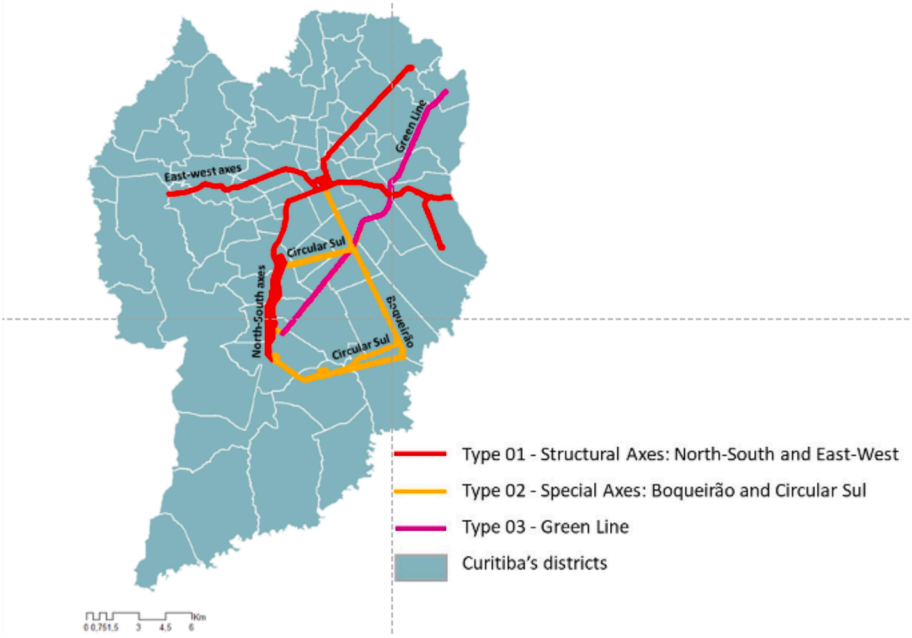

Fig. 2. Map of Curitiba's TOD / BRT corridors by type. 2019. transit network information and IPPUC (2019) land price.
Source: Prepared by the authors based on URBS (2021)

Table 1
Curitiba's transportation corridor types and its construction limits, related to land uses according to current zoning law.

TYPE OF TOD / BRT CORRIDOR	CONSTRUCTION LIMITS			
	Housing	Commercial	Mix-use	
Type 01	4*	4	4	TOD
Type 02	1	1		BRT
Type 03	1	1		BRT

Notes: The numbers in the table multiples the plot area to define the construction limits.
* It is possible to buy Building potential up to 6.
Source: Curitiba (2020a).

All the data on population, socioeconomic characteristics, land use and accessibility estimates used in this paper were originally generated by the Access to Opportunities Project (Pereira et al., 2019). These data were made publicly available by the authors at ≪https://github.com/ipeaGIT/aopdata≫.[3] We describe below the data sources and methods deployed by Pereira et al. (2019).

The method used in the project combined data from national household surveys, administrative records from federal and municipal governments, satellite images and collaborative mapping data to estimate accessibility at a high spatial resolution. The project divides Curitiba's territory into hexagonal cells, as the spatial unit of reference for aggregation of demographic, land-use and accessibility estimates.

[3] More information about the Access to Opportunities Project and its databases are available at: https://www.ipea.gov.br/acessooportunidades/en/.

The analysis was based on a hexagonal grid corresponding to the global H3 index at resolution 9, with an area of 0.11 km^2; this is the approximate size of a typical city block.[4]

Population and socioeconomic data processed by Pereira et al. (2019) come from the latest Brazilian population census, conducted in 2010. Data on per-capita household income were extracted from census figures, while population count data were extracted from a regular 200-meter grid (IBGE, 2016). These data were spatially re-aggregated using dasymetric interpolation to calculate the number of residents and average per-capita household income for each hexagonal cell.

Data on formal employment provided by Pereira et al. (2019) come from the Ministry of Labor's 2019 Annual Report on Social Information (RAIS), covering all companies with more than 10 employees. Public jobs were excluded from the analysis because of systematic inconsistencies in the addresses reported by the public sector. Geolocated data on healthcare facilities for 2019 come from the National Register of Health Care Facilities (CNES), which covers all free primary, ambulatory care and hospital services through the public health system (SUS). Data sets for job opportunities and healthcare facilities were both geocoded and made publicly available by Pereira et al. (2019).

Finally, transport information was based on GTFS transit data from October 2019, provided by Curitiba's urban planning company (URBS). These data were processed with street network data from OpenStreetMap using OpenTripPlanner (OTP) to generate accessibility estimates.

4.2. Accessibility estimates

Accessibility indicators are commonly used in urban and transport studies to indicate the ease with which people can reach places or opportunities (Van Wee and Geurs, 2011). This paper uses the accessibility estimates based on the number of employment opportunities and healthcare facilities reachable by public transport within 30, 60, 90 and 120 min. These data were made available by Pereira et al. (2019) and reflect how easily individuals could access these essential activities by transit.

This indicator is known as the cumulative opportunity measure, presented in Equation 1. This accessibility measure is one of the most widely used accessibility metrics in transport planning and equity analysis, because it is easily calculated and interpreted by policy makers (Boisjoly and El-Geneidy, 2017; Manaugh et al., 2015).

We considered a travel-time threshold of 60 min, which seems a good to fit travel behavior in Curitiba given the average travel patterns in the city. The latest 2016 household travel survey (IPPUC, 2017) indicates that public-transport journeys to work and health services in the city of Curitiba took an average of 52 and 51 min respectively.

$$CMA_{oTP} = \sum_{o=1}^{n} P_d f(t_{od})$$

Where:

CMA_{oTP} is the active cumulative opportunity estimate from origin o within time threshold T to the opportunity P.

P_d is the number of opportunities (jobs, healthcare facilities or schools) in destination d.

t_{od} is the travel time (minutes) from origin o to destination d.

$f(t_{od})$ is a time threshold function that varies between one and zero, depending on whether travel time is larger or smaller than time threshold T.

In the next section we use these data and methods to examine how Curitiba's BRT corridors are associated with the spatial distribution of real-estate values, population density and income levels, together with how these corridors shape social and spatial inequalities of access to opportunities. The code to reproduce the data analysis and figures presented in this paper was written in R it is available at ≪*link not disclosed yet to preserve the authors' identities*≫.

5. TOD and urban spatial inequalities

5.1. Population density and TOD in Curitiba

One of the main objectives of the TOD plan adopted by Curitiba is the orientation of population density along the transport axes. Despite decades of land-use policies in Curitiba allowing greater construction potential along the structural axes, the consolidation of higher population density can only be seen in those sections of TOD near the city center (Fig. 3A). Fig. 3B shows a slightly higher population densities in areas up to 300 m from the BRT corridors, but between 300 m and 10 km, densities remain constant. In short, the proposal of linear urban growth determined by high construction potential along the structural axes occurred to a limited extent in the central areas of TOD corridor, not along its full length.

The lower density along the BRT corridors indicates that the legislation with greater construction limits along the corridors, that applies to North-South and East West TOD axes (Type 01 in Fig. 2), has not been sufficient to promote higher densities. This also suggests that Curitiba's TOD policies have not managed to stimulate the full occupation of the structural axes, beyond real state natural interest. On the North axis, for example, only 10 % of the construction potential has been realized according to planned density limits (Penteado et al., 2019, p. 14).

The low population density along the non-central areas of structural axes and the current higher rates of demographic growth in peripheral areas, not served by BRT shows that the policy of linear density works only in central high-income areas, and that it is not oriented to mixed housing. This scenario prompts inquiries regarding the realization of the *Plano Preliminar de Urbanismo*, which, in 1966, laid the foundation for Curitiba's TOD strategy, primarily aiming to catalyze a linear distribution of population density along its axial corridors. It justifies questioning the extent to which the planning orientation to densify the structural axes is enough to induce the occupation, and why the occupation of TOD corridors is limited to central areas.

5.2. Spatial distribution of income levels and TOD in Curitiba

The spatial distribution of construction potential and BRT corridors defined in Curitiba's TOD have an important relationship with the spatial distribution of income groups in the city. Most of the highest-income residents live near the city center and the TOD (BRT Type 01) corridors (Fig. 4A). Meanwhile the low-income population is mainly located in the peripheral regions not covered by the BRT networks, which entails lower access to the mass transit system.

Fig. 4B also shows the relationship between income levels and proximity to the TOD axis. Although some high-income neighborhoods are further from the BRT system, an inverse relationship can clearly be seen between income and distance from the BRT system. The higher the income level, the nearer the population is to Curitiba's BRT system. On the periphery, where population growth has been highest since 2000, there is no BRT and income levels are substantially lower (IPPUC, 2012).

5.3. Real-estate values and the TOD in Curitiba

As in the case of spatial distribution of high-income groups, land prices are also substantially higher in the city center. Property prices in Curitiba are considerably higher in central areas near the presence of BRT and with high construction limits (Fig. 5A). The spatial organization of the real-estate market in Curitiba shows a clear pattern with higher priced properties nearer the North-South and East-West BRT

[4] More info about the H3 indexing system at https://h3geo.org/docs/core-library/restable.

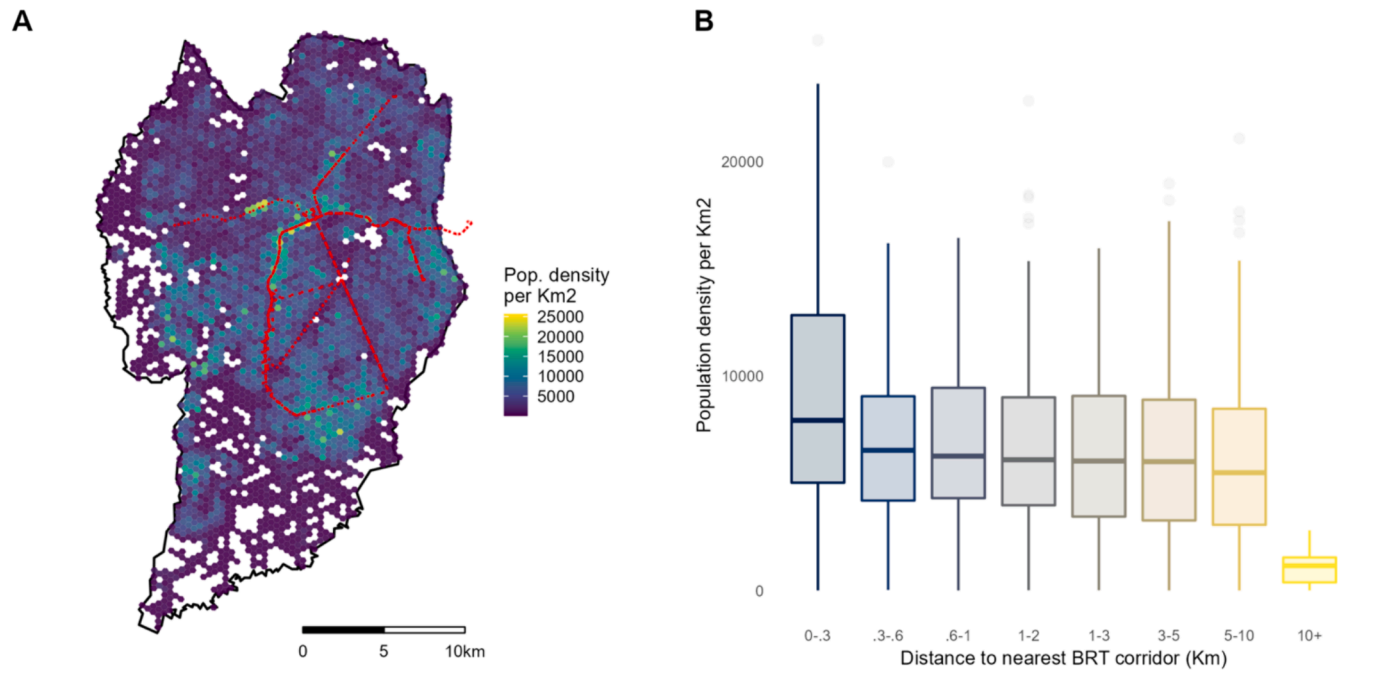

Fig. 3. (A) Spatial distribution of population density, and (B) relationship between population density and distance to the nearest BRT corridor, Curitiba, 2019. .
Source: population data 2010 census (IBGE) and BRT corridors operational in 2019

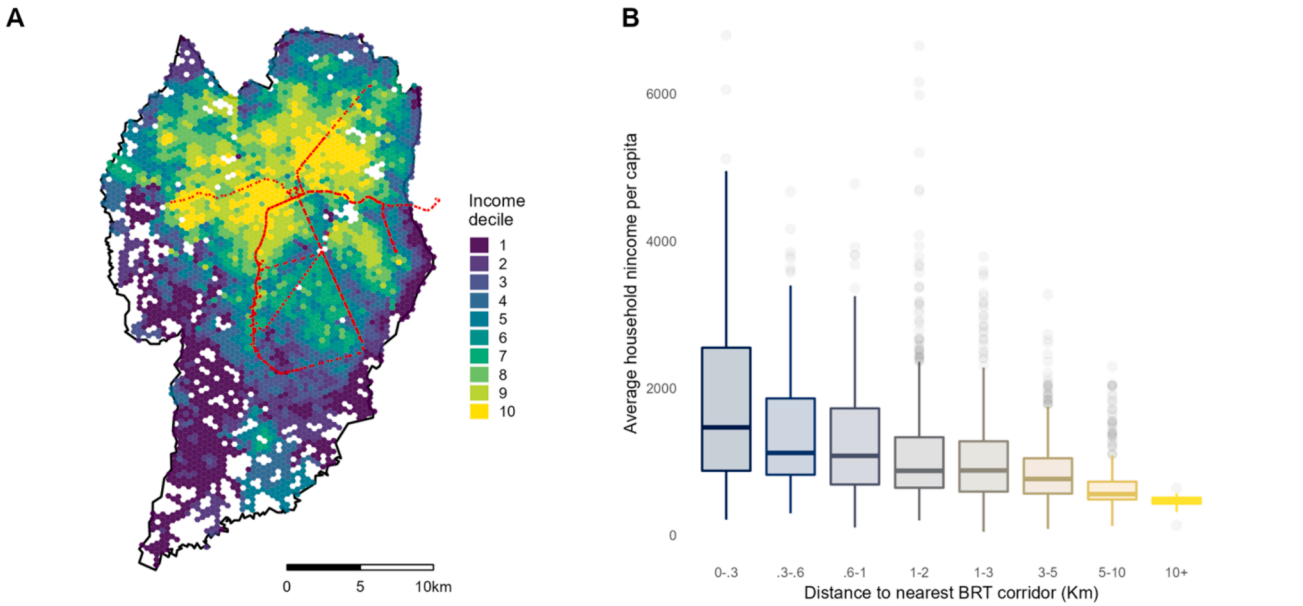

Fig. 4. (A) Spatial distribution of population by income deciles, and (B) relationship between population income and distance to the nearest BRT corridor, Curitiba, 2019. .
Source: population data 2010 census (IBGE) and BRT corridors operational in 2019. Obs. 1st income deciles comprises the 10% poorest population, while the10th decile groups the 10% wealthiest population

corridors, particularly along the TOD axes.

5.4. TOD and the distribution of accessibility benefits

Public transport accessibility to employment opportunities and health services is substantially greater along the high-capacity BRT corridors that provide superior service levels and better connectivity to opportunities (Fig. 6A and 7A). The radial shape of Curitiba's transport system also means significantly higher network connectivity to the city center, which helps perpetuate patterns of concentration in the central regions of the city.

Concentration of high-income classes along the BRT system, coupled with peripheralization of low-income classes who cannot afford to live near TOD corridors, results in marked inequalities of access to city opportunities (Fig. 6B and 7B). In 2019, the wealthiest 10 % of Curitiba's population had access to 2.6 times more jobs than the poorest 40 %, on average (Fig. 6B). Similarly, public-transport access to healthcare facilities was 2.3 times higher among high-income groups compared to the poorest (Fig. 7B).

One of the most remarkable aspects of Curitiba's BRT corridors, after

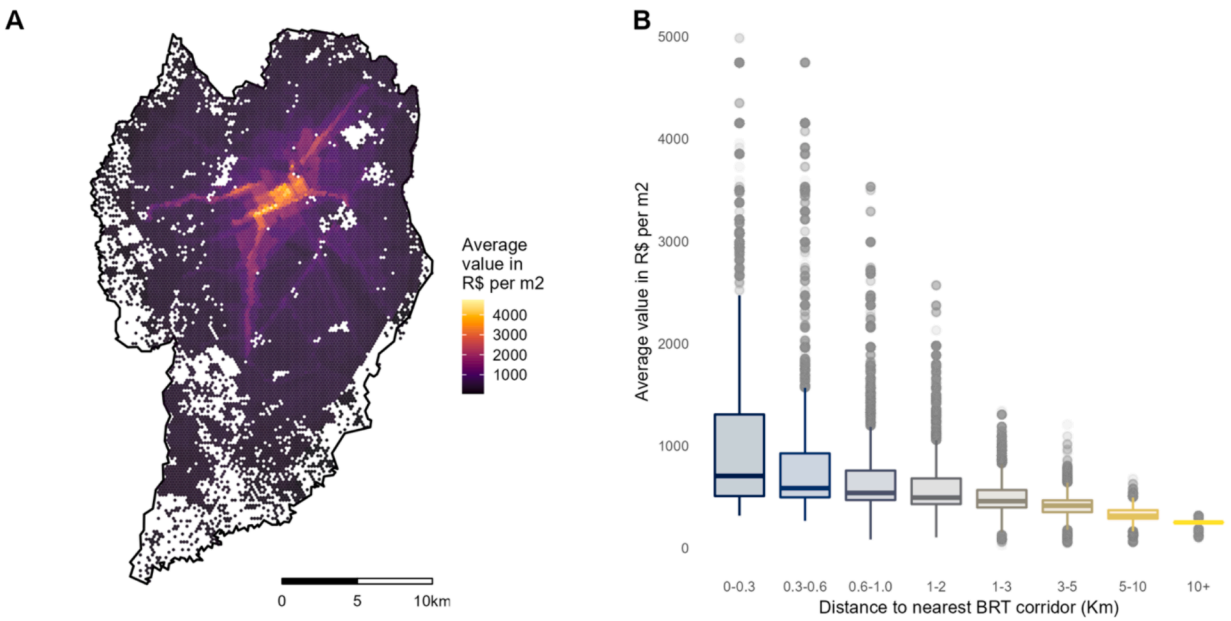

Fig. 5. (A) Spatial distribution of property values, and (B) relationship between property values and distance to the nearest BRT corridor, Curitiba, 2019. . Source: population data 2010 census (IBGE) and BRT corridors operational in 2019

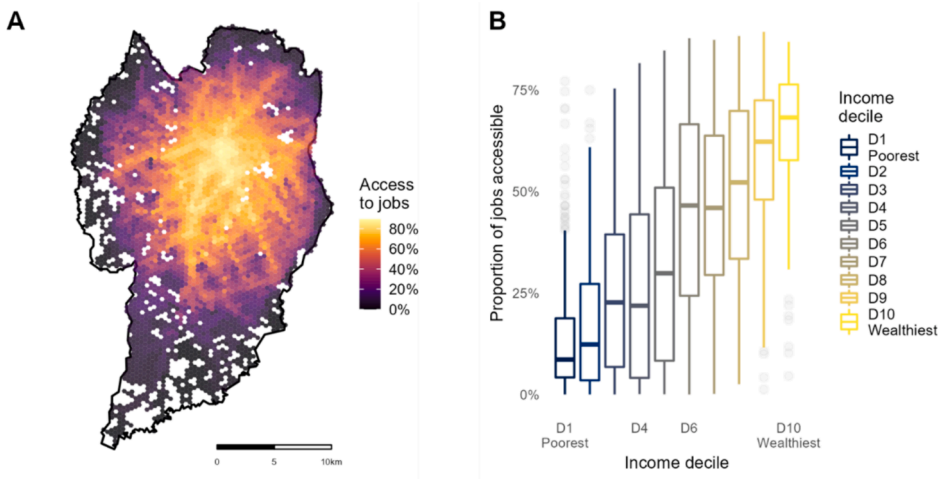

Fig. 6. (A) Spatial and (B) Income distribution of the percentage of job opportunities accessible by public transport in 60 min, Curitiba, 2019.

almost fifty years of its initial implementation, is that urban areas where the TOD is consolidated are not occupied by users of public transportation, but by users of private motorized vehicles. According to Curitiba's latest household survey data (IPPUC, 2017), the population living along BRT corridors uses motorized private vehicles in more than 80 % of their daily trips. This shows that the sole presence of TOD has very little, if any, effect on decreasing motorization. Curitiba's household survey also shows that the lower-income population (with an average income limited to one minimum wage), living in peripheral neighborhoods, travel significantly more by public transportation than by private motorized vehicles.

Another aspect to be highlighted is the remarkably higher passenger demand of the South corridor of the TOD in comparison with the other axes, particularly because this area is not marked by a high-density rate. This indicates higher stress of the public transport system in areas where the population lives further away from BRT corridors and must use other bus lines to reach the mass transit system. These are also the regions of the municipality (South and South-West) that concentrates most of the low-income population.

In summary, the TOD in Curitiba has not been successful in defining high-density areas along the corridors, except in areas near the city center. Additionally, the TOD contributed to the concentration of premium real estate market along BRT corridors, what contributes to push low-income communities to peripheral urban areas less served by public transport and with lower access to economic opportunities and health services.

6. Final remarks

This study helps to demystify the acclaimed success of Curitiba's BRT as a driver of urban sustainability, by showing that its TOD planning contributes to shape social segregation and inequalities of access to opportunities. The TOD in Curitiba has knock-on effects on land prices, that hinders the social mix purported as a TOD policy benefit, reinforcing spatial disparities between center and peripheral urban areas. The clearest effects of TOD on the spatial organization of the city are the patterns of high-income occupation and higher land prices along the corridors. The development of a premium real-estate market alongside

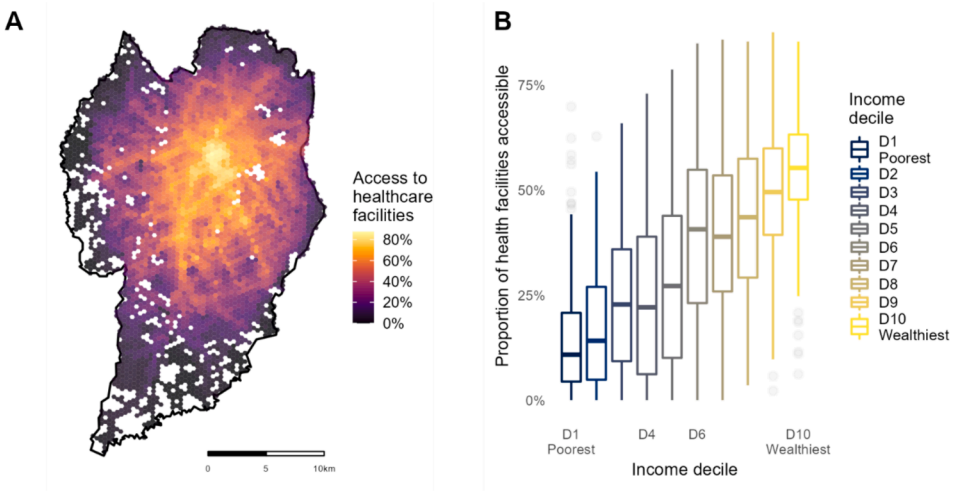

Fig. 7. (A) Spatial and (B) Income distribution of the percentage of healthcare facilities accessible by public transport in 60 min, Curitiba, 2019.

TOD corridors, particularly those nearest to the center, is one of the main results of this urban policy.

The structural axes, formed by the TOD lines, lanes dedicated to individual vehicles and special land-use policy, concentrate the BRT infrastructure, parallel high-speed roads and greatest building potential, which leads to higher land values in the immediate surroundings of the mass transit system. The areas nearer the city center are more consolidated, with concentrations of high-income populations alongside the TOD corridors. The areas served by TOD, but further away from the central areas are increasingly less densely occupied, with clusters of vacant land (Penteado et al., 2019) that suggests real-estate market speculation. High property values in the central area of the city and the growth of new urban densification on the periphery reflect the expansion of lower-income housing towards the periphery where real-estate is more affordable. Historically, Curitiba's TOD policies have not been able to promote socioeconomic diversity along the corridors (Duarte and Ultramari, 2012; Fernandes and Firkowski, 2014), and has contributed to urban sprawl and social segregation.

Combined, these characteristics of the TOD policy in Curitiba have led to an unequal urban environment with important equity implications. Despite the potential to create inclusive communities, the TOD corridors in Curitiba are restricted to few limited areas that concentrate income, resources, and opportunities. Therefore, we find remarkable levels of inequalities in access to opportunities in the city. We find that access to employment opportunities and healthcare services is up to 2.6 times lower for low-income groups than for the wealthier population. This accessibility gap is partially explained by the concentration of opportunities and resources in central areas and those areas directly served by the BRT, but it is also a consequence of the peripheralization of lower-income population, pushed to regions with more affordable housing that are less served by public transport and further from the opportunities in city center.

One limitation of our study is that, given the limited historical data availability, we cannot ascertain the extent to which the unequal appropriation of TOD's benefits by income classes today occurs because the TOD pushed low-income munities away, and the extent to which it was because the TOD corridors were originally built in predominantly high-income neighborhoods. In practice, though, it is likely to be a combination of both processes given the self-reinforcing mechanism between transport and land use developments. Nonetheless, our findings go in line with previous studies that criticize TOD projects for having exclusionary effects due to increased land prices and unequal opportunities for housing and accessibility (Saunders and Smith, 2014; Jamme et al., 2019, Laake and Quiñones, 2019). Our findings suggest that Curitiba's planning should be analyzed more critically, and that Curitiba's success story should be seen as a cautionary tale about the unintended consequences of TOD planning with strong coordination between transport and land-use policies.

To mitigate the negative effects of TOD and BRT projects discussed in this paper, it is important that new similar projects in Curitiba and elsewhere adopt transport accessibility-oriented and equity goals coordinated with social housing policies. A general policy lesson from some of the BRT corridors in Curitiba is that investments in BRTs alone are not sufficient to gear urban development towards a TOD approach. In other words, the purported benefits of TOD in terms of promoting linear densification and decentralization in urban development cannot be easily achieved simply with mass transit investments.

Moreover, Curitiba illustrates that even a successful case of coordination between land use policies and mass transit investments in a few BRT corridors are not sufficient to promote equitable TOD. Future TOD projects need to seriously incorporate social housing goals in to make sure that low-income families can live closer to mass transit corridors and that the transit accessibility benefits from TOD are more equitably distributed. This more integrated strategy, we argue, can be based in three dimensions: (i) mixed housing policy along BRT corridors, mainly in the non-central areas, where there is land stock, (ii) rapid transit connection with peripheral areas, where public transportation users are concentrated, and (iii) decentralization of job opportunities and services by local economic development policies in non-central areas.

By increasing population and land-use densities near transit corridors, TOD policies have the potential to increase public transport ridership. Nonetheless, without the necessary planning controls needed to ensure a diversity of housing types, housing affordability and employment within transit corridors to ensure that all social groupings enjoy the benefits of improved public transit, the potential ridership benefits of TOD are likely to remain limited.

CRediT authorship contribution statement

André L.B. Turbay: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Project administration, Visualization. **Rafael H.M. Pereira:** Conceptualization, Methodology, Software, Validation, Data curation, Writing – review & editing, Supervision, Visualization. **Rodrigo Firmino:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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