Revista Brasileira de Cartografia
ISSN 1808-0936 | https://doi.org/10.14393/revbrascartogr
Sociedade Brasileira de Cartografia, Geodésia, Fotogrametria e Sensoriamento Remoto

Evaluating the Usability of the TOPODATA DEM to Measure Cyclist Accessibility: A Case Study of a Small Town

Avaliação da Usabilidade do MDE TOPODATA para Mensurar a Acessibilidade de Ciclistas: Um Estudo de Caso para uma Cidade Pequena

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Received: 03.2022 | Accepted: 06.2022

Abstract: Devising urban mobility plans for Brazilian cities, especially small ones, lacks technical support, such as altimetric surveys that allow the representation of the terrain accurately, causing many transportation planners to benefit from Digital Elevation Models (DEMs). This study aims to evaluate the usability of TOPODATA DEM to measure the accessibility of cyclists to their potential travel destinations. A case study was conducted in the city of Bariri-SP (Brazil), where altimetric data collected using GNSS technology was previously available. Expected speeds for cyclists were assigned to the road segments as a function of their respective TOPODATA and GNSS slopes, allowing the identification and comparison of the shortest homologous paths between the units of analysis and bicycle Trip Attractors (TAs). The homologous accessibilities in each unit of analysis were also compared with each other, and the differences between them were evaluated according to their spatial autocorrelation, in addition to their spatial dependence on TOPODATA altitudes and slopes. The impact on the overall accessibility of different population groups in the city when using the DEM was also observed. The results suggest the shortest homologous paths that are quite similar to each other, although the accessibility samples for both sources of altimetric information differ statistically. A strong spatial autocorrelation was observed between differences in homologous accessibilities, but moderate to weak spatial dependences were observed between this variable and TOPODATA altitudes or slopes. The overall accessibility of each evaluated population group is similar regardless of the criterion used.
Keywords: Bicycle. Accessibility. DEM. TOPODATA. GNSS.

Resumo: A elaboração de planos de mobilidade urbana para as cidades brasileiras, principalmente as de pequeno porte, carece de subsídios técnicos, como levantamentos altimétricos que permitam representar o relevo de forma precisa, fazendo com que muitos planejadores em transportes recorram a Modelos Digitais de Elevação (MDEs). Este trabalho tem o objetivo de avaliar a usabilidade do MDE TOPODATA para mensurar a acessibilidade de ciclistas a seus potenciais destinos de viagem. Um estudo de caso foi conduzido em Bariri-SP, onde dispunha-se previamente de dados altimétricos levantados com a tecnologia GNSS. Velocidades esperadas para os ciclistas foram atribuídas aos segmentos viários em função de suas respectivas declividades TOPODATA e GNSS, permitindo identificar e comparar os caminhos mínimos homólogos entre as unidades de análise e Polos Geradores de Viagem (PGVs) por bicicleta. As acessibilidades homólogas, em cada unidade de análise, também foram comparadas entre si e as diferenças entre elas foram avaliadas de acordo com sua autocorrelação espacial, além de sua dependência espacial com relação às altitudes e declividades TOPODATA. O impacto à acessibilidade geral de diferentes grupos populacionais de Bariri-SP, quando utilizado o MDE, também foi verificado. Os resultados sugerem caminhos mínimos correlatos bastante semelhantes entre si, apesar das amostras de acessibilidades para ambas as fontes de informações altimétricas divergirem estatisticamente. Observou-se uma forte autocorrelação espacial entre as diferenças de acessibilidades homólogas, porém dependências espaciais de moderadas a fracas entre esta variável e as altitudes ou declividades TOPODATA. A acessibilidade geral de cada grupo populacional avaliado é similar inobstante ao critério utilizado.
Palavras-chave: Bicicleta. Acessibilidade. MDE. TOPODATA. GNSS.

1 INTRODUCTION

In Brazil, initial efforts aimed at cycling planning on a national level resulted from the first oil crisis, in the 1970s, when restrictions were imposed on motor vehicles (BRAZILIAN MINISTRY OF CITIES, 2007). Since then, cycling policies such as the Brazilian Bicycle Mobility Program have been important, but not sufficient to provide technical support that helps, for example, to devise urban mobility plans. It can also be observed that several recent events have brought to light the discussion on the panorama of urban mobility in Brazil, such as the popularly called "*Jornadas de Junho*" (demonstrations against rising public transport fares) in 2013, and the "Truck drivers' Strike" in 2018 (ANDRADE et al., 2016; MONARI et al., 2018). Similar to this, the Coronavirus (COVID-19) pandemic, officially declared in Brazil at the beginning of 2020, also had an impact on Brazilian cycling activism. It is estimated that bicycle sales increased by 34.17% in the first half of 2021 compared to the same period in the previous year (ALIANÇA BIKE, 2021), which can be partially explained by many users migrating from public transport to active transportation to avoid agglomerations.

However, loyalty of new cyclists poses a challenge, as authors such as Aldred and Jungnickel (2014) argue that bicycle use, in addition to the existence of bike paths and bike lanes, is stimulated by a cultural issue. Even in the smallest Brazilian municipalities, where a "bicycle culture" has always been assimilated, there are well-known consequences of prioritizing motorized transport, especially regarding the phenomenal growth of the number of motorcycles over the last decade, stimulated, among other reasons, by a reduction in the Tax on Industrialized Products (IPI in Portuguese) and other economic and fiscal stimuli by the Brazilian federal government (SOARES; GUTH, 2018).

In this context, although Brazilian transportation authorities are ready to help reverse this situation, it is essential that federal transfers are carefully allocated in cities of different sizes with well-known cycling potential, and not only, as in practice, in metropolitan regions (RUBIM; LEITÃO, 2013; LOURENÇO; BOSCO JÚNIOR; BERNARDINIS, 2019). Furthermore, in Brazil, information indispensable for transport territorial planning is also restricted to these larger municipalities, such as origin-destination surveys, georeferencing of road accidents, traffic counts, urban pavement management systems and altimetric surveys for accurate representation of the terrain. Regarding the latter, however, Digital Elevation Models (DEMs) are customarily used to fill the need for technical support, such as that provided by the Brazilian National Institute for Space Research (INPE-Brazil), entitled TOPODATA.

The TOPODATA model is a DEM derived from the Shuttle Radar Topography Mission (SRTM) data. The SRTM mission was undertaken in February 2000 in partnership between the US National Aeronautics and Space Administration (NASA), the German Aerospace Center (*Deutsches Zentrum für Luft- und Raumfahrt*, or DLR) and the Italian Space Agency (*Agenzia Spaziale Italiana*, or ASI), and benefited from interferometry technology, that is, altimetric data acquisition through two SAR (Synthetic-Aperture Radar) antennas separated by a 60-meter extender device (FARR et al., 2007), covering about 80% of the Earth's surface.

Concerning South America, the SRTM model was originally made available with a spatial resolution of 90 meters, but after reprocessing these data (interpolation) throughout the entire Brazilian territory, INPE made the TOPODATA DEM available in 2004, whose spatial resolution is 30 meters (VALERIANO; ROSSETI, 2012), not in terms of sample spacing, but "pixel size" of the raster layer offered to Geographic Information System (GIS) users. Thus, despite maintaining the geomorphological properties of the original model, TOPODATA geospatial data must be evaluated regarding their logical consistency, completeness, positional and temporal accuracies and, for cycling planning purposes, above all, their usability, or that is, whether such data meet the specifications of a particular application of interest to the user (ARAÚJO, 2016; IBGE, 2017).

The present work aims to evaluate the usability of the TOPODATA DEM to measure the accessibility of cyclists to potential bicycle Trip Attractors (TAs). A case study was conducted in the city of Bariri-SP (Brazil), for which previous altimetric surveys were available (leveling of road segments using the Global Navigation Satellite System - GNSS technology) to compare both sources of altimetric information while identifying the fastest routes (shortest routes) to these TAs, assuming that the speed of cyclists is directly influenced by the slope of the road segments on which they travel (TOOLE, 2010). Thus, the following questions must be answered:

a) What is the difference, in relative percentage terms, between the shortest homologous paths, identified based on the TOPODATA DEM and on altimetric data collected in the field, to access bicycle TAs?

b) Is there a significant difference between the accessibility of cyclists to bicycle TAs when measured based on the TOPODATA DEM and on altimetric data collected in the field?

c) Is it possible to identify any spatial pattern in the differences between homologous accessibilities?

d) When weighting the accessibility in each unit of analysis by the resident population, does the TOPODATA DEM reflect an overall accessibility different from that calculated for the field data?

Due to the methodological approach of research (reproducibility to other study sites or using other DEMs), selecting the TOPODATA model is justified solely because it is one of the most familiar and widespread DEMs among Brazilian researchers and professionals. It is essential to point out, however, that other DEMs are also currently available for transport territorial planning. The 2020 NASADEM, for example, consists of reprocessing SRTM data to fill gaps in elevations existing in previous models, such as TOPODATA DEM itself, ensuring better altimetric accuracy (NASA JPL, 2020; SILVA; RANGEL; CAMPOS, 2020). Free models designed from photogrammetry, such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the ALOS World 3D-30m (AW3D30), have global coverage and spatial resolution similar to their peers (CARRERA-HERNÁNDEZ, 2021). The TanDEM-X, similar to the SRTM, was also produced from radar interferometry (but using two satellites in controlled formation), and despite having a spatial resolution of 12 meters (DONG et al., 2021), it consists of a commercial DEM. However, derivations of the latter with spatial resolution similar to other DEMs (30 meters) are free of charge, such as the Copernicus-DEM (CENCI et al., 2021) and the Forest and Buildings removed Copernicus-DEM, or FABDEM (HAWKER et al., 2022).

2 LITERATURE REVIEW

Accessibility is the ease of reaching travel destinations (HANSEN, 1959), and it is understood that such ease is inversely proportional to the distance or travel time. Travel time is a factor that greatly influences not only individuals' decisions to use a bicycle as a mode of transportation, but also to choose the route they wish to travel on (AULTMAN-HALL; HALL; BAETZ, 1997; STINSON; BATH, 2003; MENGHINI et al., 2010; SEGADILHA, 2014). Although intrinsically related to the physical conditioning and age of the cyclists, this variable is also related to the characteristics of the road itself, whether geometric, operational or related to its surroundings, as cyclists seek whenever possible to deviate from road segments characterized by adverse conditions, aiming to maintain a homogeneous level of safety and comfort on their trips (HOOD; SALL; CHARLTON, 2011; BROACH; DILL; GLIEBE, 2012).

In this context, road slopes (ramps) are repeatedly cited in the literature as potential barriers to cycling (SENER; ELURU; BATH, 2009; WINTERS et al., 2010). Steep upslopes require great physical effort and energy expenditure from cyclists, while steep downslopes hinder road safety by making it difficult for cyclists to maintain balance. However, unlike other factors that influence cycling as a mode of urban transport, for which technical solutions can be applied (high speeds of motorized traffic can be mitigated by effective electronic inspection, dangerous intersections can receive adequate treatment, the availability of space can benefit from vehicle parking restrictions, etc.), it is not always possible to modify the road grade to make it bicycle-friendly, due to physical and budgetary restrictions (built environment, earthwork costs, etc.). Thus, whenever possible, it is recommended that cycling routes be planned on paths with slopes limited to a rate of 3% (CHIPS, 2021), with values of up to 5% still being admissible (AASHTO, 1999), and for cases where this premise cannot be complied with, steeper slopes should be evaluated according to their respective cycling acceptable lengths of gradient (FHWA, 1977; AUSTROADS, 2014).

Despite this well-known importance of terrain characteristics for cycling planning, the lack of accurate topographic maps produced from ground-level surveys leads many transportation planners to benefit from DEMs (ZIEMKE; METZLER; NAGEL, 2017; MASRI; BIGAZZI, 2019). In Brazil, for example, authors such as Neri (2012) and Simeão, Manzato and Viviani (2019) benefited from these digital cartographic products to, respectively, plan and assess the adequacy of cycling networks; and others such as Magalhães, Campos and Bandeira (2015) and Monari, Segantine and Silva (2019) aimed to identify cycling routes by assigning impedances to road segments according to their respective slopes extracted from DEMs. In addition, several of the international studies that have aimed to measure the accessibility of cyclists to bicycle TAs, mainly over the last decade due to the increasing evolution of GIS, have benefited from assessing the terrain characteristics of the studied area.

Winters et al. (2013) listed five different parameters for the composition of a bike score index. Among them are the terrain characteristics that, for a case study conducted in Vancouver (Canada), were obtained from a DEM with a spatial resolution of 30 meters. In a case study in Graz (Austria), Krenn, Oja and Titze (2015) proposed a bikeability index that accounted for the topographic conditions of the terrain of a unit of analysis in terms of the average slope class within a given region of influence of 200 meters from it. Lin and Wei (2018) measured the relative cycling potential between traffic zones in the Daan district of Taipei (Taiwan) that had the worst evaluated regions affected by hilly terrain.

Lowry, Furth and Hadden-Loh (2016) aimed to identify road segments that ensure connectivity between residential areas and bicycle TAs in Seattle (USA). To do this, in addition to being classified according to their Level of Traffic Stress, road segments were also assigned slope factors according to Marginal Rates of Substitution (MRS) proposed by Broach, Dill and Gliebe (2012), that is, it is estimated that cyclists are willing to travel up to 37% more to avoid upslopes between 2% and 4%; 120% more, for upslopes between 4% and 6%; and 323% more, for upslopes steeper than 6%. The results allowed the identification of regions with restricted accessibility.

In a study conducted in Portland (USA), Ma and Dill (2017) investigated possible reasons for the disagreement among other studies in the literature on the relationship between the objectively "measured" cycling potential as a function of built environment attributes, and "perceived" subjectively by cyclists. Regarding the former, one of the attributes considered in the work was the percentage of the area of influence of a unit of analysis (network distance of one mile) with slopes steeper than 25%. The results suggest that the divergence between objective and subjective cycling potentials may be related to the type of trip and that for utilitarian trips both play an important role.

In a study conducted in Basel (Switzerland), Grigore et al. (2019) analyzed the influence of terrain characteristics and other factors on the accessibility of cyclists, according to technical standard guidance on how steep slopes reduce the speed of cyclists going up ramps and increase the risk of accidents involving cyclists going down ramps. The results point to a limited impact of the provision of cycling infrastructure on the accessibility of the studied cyclists, who are possibly more sensitive to travel distances and terrain slopes.

3 MATERIALS AND METHOD

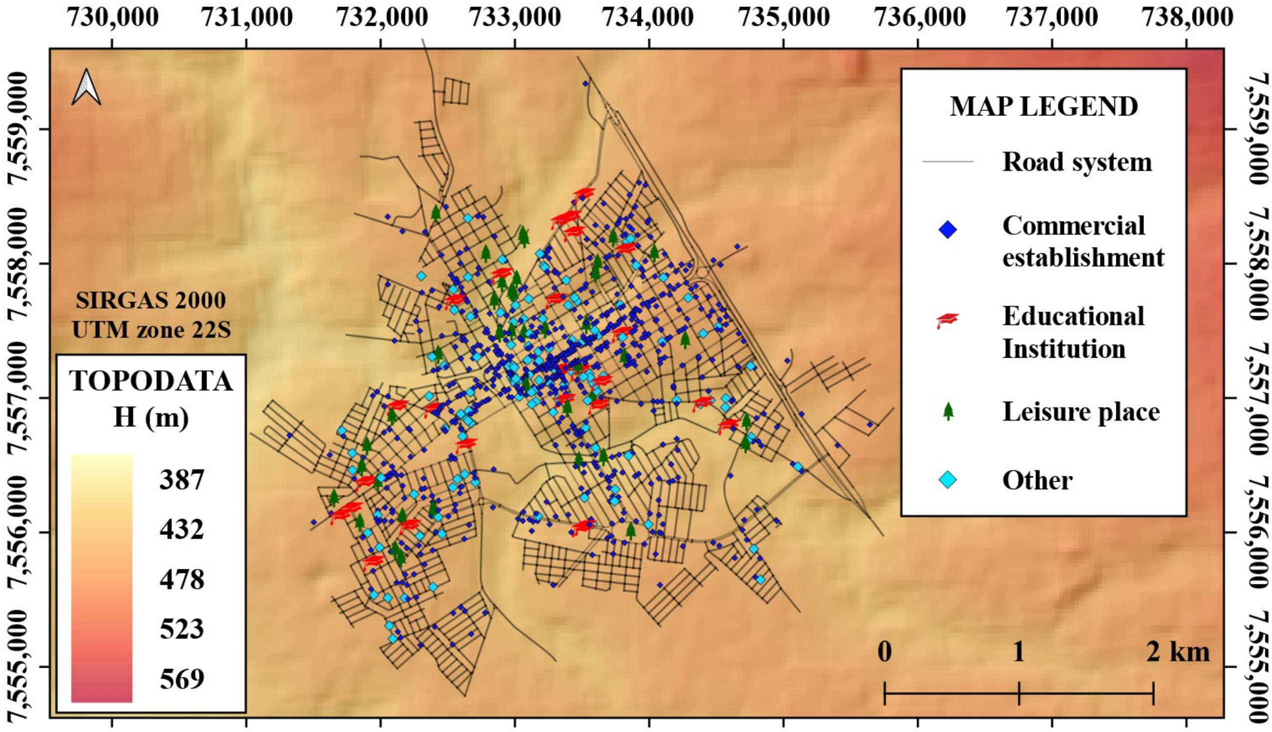
This section presents the materials and method of this research. It is worth mentioning that in practically all stages, the QGIS software version 3.8.2 "Zanzibar" was used for spatial data geoprocessing, an open source GIS available for free to download.

3.1 Case study data

Figure 1 presents the TOPODATA DEM referring to the city of Bariri (Brazil), located in inland São Paulo state, and belonging to the Bauru-SP mesoregion. Its current population is estimated to be 35,844 inhabitants (IBGE, 2021). According to the classification proposed by the Brazilian Agricultural Research Corporation (EMBRAPA, 1979), just over 62% of the urban area of the municipality is evaluated as flat terrain (slopes of less than 3%), about 37% as smoothly undulating terrain (slopes between 3% and 8%), and the small remainder as moderately undulating terrain (slopes between 8% and 13%).

To represent the road system of the case study, open data from the OpenStreetMap (OSM) collaborative mapping platform were used. In total, as also shown in Figure 1, 2,261 vector features corresponding to the road segments of the city of Bariri-SP were filtered, which were submitted to topological validation and evaluated according to their permitted traffic directions. In this last step, the QGIS routing plugins require the user to specify numerical values characteristic of the different movements in the network, that is, forward, backward, or in both directions, in a column of the attribute table, generally standardized, in this order, as 1, -1 and 0. To do this, first of all, the traffic directions allowed in each road segment were identified through ground-level navigation on the Google StreetView platform. Then, knowing that upward and downward movements in the network must be evaluated differently (for example, a "two-way" road segment with a slope of 3% allows cyclists to go up a ramp of +3% or, in the opposite direction, to descend a ramp of -3%), the road segments that allow traffic in both directions were duplicated, and each of the overlapping segments was assigned a single traffic direction. Thus, the final network of the case study was increased to 3,900 road segments ("edges"), which intersect or end in 1,428 "nodes", constituting a graph. Finally, the joint analysis of the traffic direction of each road segment in this final network and the altitudes of their respective initial and end nodes, extracted from the TOPODATA DEM through the QGIS Point Sampling Tool, allowed calculating their average slopes.

Figure 1 – Bariri-SP: TOPODATA DEM, road system and bicycle TAs.



Source: Authors (2022).

The potential bicycle TAs in the city of Bariri-SP were georeferenced through a systematic search for these facilities on the Google Maps platform. It is important to note that at this stage, the few industries or factories of the studied city were not considered. This can be explained by the fact that these specific TAs are closely related to commuting, to which cyclists are typically willing to travel longer distances or for longer periods to access them when compared to other types of facilities (DILL; GLIEBE, 2008; KRIZEK; FORSYTH; BAUM, 2009). Therefore, some authors in the literature argue that work accessibility measures may not reflect cyclists' ability to reach important travel destinations, such as supermarkets, schools, leisure places, etc. (MCCAHILL, 2018), while non-work accessibility measures can help territorial transport planning as they are good predictors of local travel and physical activity (MERLIN, 2014; CHUDYK et al., 2015).

Considering this, four different categories of bicycle TAs were listed: 1) Commercial establishment, 2) Educational institution, 3) Leisure place and 4) Other, each of which is also stratified into subcategories, as further explained in the following sections. In total, 950 potential TAs were georeferenced, as also shown in Figure 1.

Regarding the units of analysis to measure cyclists' accessibility, it was chosen a set of regular georeferenced cells (200 x 200 meters) that integrate the so-called statistical grid, made available by the

Brazilian Institute of Geography and Statistics (IBGE-Brazil). Aggregated population data (age and income) by census sectors were obtained from the results of the 2010 Brazilian Demographic Census and then transferred to each grid cell by weighting the area of intersection between the two vector layers. The option for the census grid is justified by the fact that larger units of analysis are subject to "ecological fallacy", that is, the assent that accessibility to bicycle TAs occurs homogeneously among all individuals residing in them (IACONO; KRIZEK; EL-GENEIDY, 2010). Thus, for the city of Bariri-SP, 475 units of analysis were filtered, corresponding to the cells of the statistical grid that comprise its urban limits.

In order to evaluate the usability of the TOPODATA DEM to measure the accessibility of cyclists at the study site, it was compared with altimetric data collected by a precise satellite method. The previously existing survey in the city of Bariri-SP consists of a leveling of the road segments through GNSS Post-Processed Kinematic (PPK) relative positioning, conducted between September 7 and 22, 2017. For this survey, two Dual-frequency GNSS receivers were used. A fixed GNSS receiving antenna (taken with a reference) was positioned close to the municipality's Wastewater Treatment Plant (WTP), which has restricted access to the public and very few obstacles such as trees and buildings. This was done to track data uninterruptedly for 9 hours, at a tracking rate of 1 second, and, consequently, to obtain the base station coordinates by adjusted baseline post-processing from 3 different active stations from the Brazilian Network for Continuous Monitoring (RBMC-Brazil) close to the study site, that is, EESC (São Carlos), SPBO (Botucatu) and SPPI (Piracicaba). The remote antenna, in turn, was transported using a vehicle through all accessible locations of the road system of the city of Bariri-SP and was also configured with a tracking rate of 1 second (simultaneous to the fixed GNSS receiving antenna). Post-processing the information benefited from the LEICA Geo Office Combined 7.0 software. Regarding the main processing parameters, a cut-off angle (α) of 15°, the tropospheric Hopfield model, and no ionospheric models were considered (SILVA; SEGANTINE, 2015; MONARI, 2018).

Having the post-processed data, all points for which ambiguity could not be solved were discarded, and the remaining ones were submitted to batch processing in the MAPGEO2015 software, available free of charge by the IBGE, to define their respective geoid undulations and subsequent conversion of their geometric heights into orthometric altitudes. Then, they were exported in shapefile format (.shp) to be geoprocessed with GIS. Thus, the altitudes of the initial and end nodes were defined, and the average slope was calculated for the vast majority of the edges of the graph, and for the locations not accessed during the field survey or whose surveyed points were previously discarded, these altitudes were interpolated using the Inverse Distance Weighting (IDW) method.

3.2 Accessibility to potential bicycle TAs

The most recurrent mathematical formulation to calculate the accessibility of a given origin zone *i* is supported by gravitational metrics adapted from the work of Ingram (1971), as presented in Eq. (1).

$$A_i = \sum_{j=1}^{n} Y_j \times f(t_{ij}) \tag{1}$$

where A_i is the accessibility of the origin zone *i*; Y_j is the relative importance of zone *j*; and $f(t_{ij})$ is the impedance function for the travel time between *i* and *j*.

3.2.1 IDENTIFYING THE SHORTEST ROUTES

The computational tools used to calculate routes, including many network analysis plugins for GIS platforms, benefit from Dijkstra's algorithm (1959) based on graph theory. Once a road system is represented by nodes and edges and the latter are assigned weights according to the time required to travel them, the shortest path between a given origin-destination pair is the one whose sequence of continuous edges minimizes the accumulated travel time complying with the movement restrictions in the network.

The travel time to cover a given road segment of the network, in turn, can be calculated by the ratio between the length of this road segment and the expected speed of cyclists along it. On the other hand, literature reviews aimed at investigating the operational speed of cyclists suggest that there is no consensus among transport authorities regarding this parameter (ALLEN et al., 1998; LIN et al., 2008), as it can vary depending on the degree of development of a country and the consequent profile of cycling demand, as well as the type of bicycle accommodation or geometric attributes of the road, such as its slope. In the latter case, in a review of the technical manual Guide for the Development of Bicycle Facilities (AASHTO, 1999) carried out by Toole (2010), some ranges of expected speeds are suggested for adult cyclists who travel under the influence of different slopes, that is, 13 to 24 km/h for flat terrain; 8 to 19 km/h for steep upslopes; and 32 to 50 km/h for steep downslopes (FLORIDA DEPARTMENT OF TRANSPORTATION, 2000; LANDIS; PETRISCH; HUANG, 2004).

Thus, considering up or downslopes limited to 3% as flat terrain, the maximum speed suggested for cycling planning purposes was adopted for this situation (24 km/h). For slopes steeper than 3%, but still admissible to cycling, that is, limited to 5%, a speed decrease of 8 km/h was considered in the case of ascents, and an increase of 8 km/h in the case of descents, resulting in speeds, in that order, of 16 and 32 km/h, consistent with the suggested interval for each situation. Similarly, in the case of slopes steeper than 5%, a variation of 16 km/h was adopted in relation to the speed for flat terrain, resulting in speeds of 8 km/h for ascents and 40 km/h for descents. Table 1 summarizes the values adopted for each situation.

Table 1 – Speeds adopted for cyclists under the influence of different slopes.

Slope	Uphill speed (km/h)	Downhill speed (km/h)
< 3%	24	24
3% - 5%	16	32
> 5%	8	40

Source: Adapted from Toole (2010).

Eq. (2) presents the impedance function considered in this work for the travel time. It is important to highlight that in similar studies in the literature, continuous decay functions in negative exponential form are normally used, which demand, however, robust data on bicycle trips in the studied place to calibrate their coefficients (IACONO; KRIZEK; EL-GENEIDY, 2010; VALE; PEREIRA, 2017; HAMIDI; CAMPOREALE; CAGGIANI, 2019). Not having these data, an alternative to define the decay function of the gravitational accessibility measure is to arbitrate and weight travel time intervals consistent with the tolerable limit for cyclists (GEHRKE et al., 2020). In this context, for the case study, the threshold defined for characterizing a particular non-work TA as accessible by bicycle is based on other research that suggests cycling-influenced environments between 15 and 20 minutes of travel (MCNEIL, 2011; HOSFORD: BEAIRSTO; WINTERS, 2022).

$$f(t_{ij}) = \begin{cases} 1.00, & \text{if } t_{ij} \leq 5 \\ 0.75, & \text{if } 5 < t_{ij} \leq 10 \\ 0.50, & \text{if } 10 < t_{ij} \leq 15 \\ 0.25, & \text{if } 15 < t_{ij} \leq 20 \\ 0.00, & \text{if } t_{ij} > 20 \end{cases} \tag{2}$$

where t_{ij} is the shortest travel time between *i* and *j*, in minutes.

3.2.2 RELATIVE IMPORTANCE OF DESTINATION ZONES

Regarding the relative importance of the destination zones, it is proposed that each bicycle TA be weighted according to the scoring system presented in Table 2. The values adopted are based on guidelines proposed in a study carried out by McNeil (2011), however, subject to some adaptations. In summary, the author relied on a study entitled US 2009 National Household Travel Survey (FHWA, 2009) to quantify the relative importance of different facilities, listed in order to integrate a complete set ("basket") of potential travel destinations by bicycle not motivated by work, so that points would be assigned to each type of destination if a minimum number of them, also stipulated by the author, were accessible at distances of up to 4 km.

Table 2 – Weighting system for bicycle TAs.

Category	Type of TA (*k*)	Weight (p_k)
Commercial establishment	Trade in specific goods (1)	2.5
	Beauty salon, hairdresser, etc. (2)	2.5
	Clothing store (3)	5.0
	Restaurant, café, bar (4)	7.5
	Supermarket or grocery store (5)	7.5
Educational Institution	Daycare (6)	2.5
	Preschool (7)	2.5
	Elementary school (8)	5.0
	High School (9)	7.5
	Higher Education (10)	7.5
Leisure place	Public square or park (11)	15
	Sports club (12)	10
Other	General services (bank, post office, etc.) (13)	7.5
	Religious organization (14)	7.5
	Health center (15)	10
Total	-	100

Source: Adapted from McNeil (2011).

In this study, similarly, for each category of georeferenced TAs, new subcategories were created, in order to also account for this relative importance between them. For example: within the category "Commercial establishment", as suggested by McNeil (2011), supermarkets are expected to attract a greater number of cyclists when compared to specific stores, such as florists, computer stores, etc. On the other hand, some TAs considered in the original publication were excluded from the scoring system because they are rare in Brazilian cities, such as Light Rail Vehicle (LRV) stops, and bus stops were not included because, in this research, it was decided not to study the integration between bicycles and public transport. Finally, some types of travel destinations considered separately in the base work were regrouped here (for example, banks and post offices now belong to a new subcategory, "General Services"), and other TAs that were previously disregarded were included, such as health units.

Once the corresponding points have been assigned to each georeferenced TA and the density of points per unit of analysis has been identified, the relative importance of each destination zone *j* can be calculated according to Eq. (3) and (4).

$$y_j = \sum_{k=1}^{15} p_k \times q_{j,k} \tag{3}$$

$$Y_j = \frac{y_j}{\sum_{j=1}^{n} y_j} \tag{4}$$

where y_j is the attractiveness potential of zone *j*; p_k is the weight of type *k* TA; $q_{j,k}$ is the quantity of type *k* TAs within zone *j*; Y_j is the relative importance of zone *j*; and *n* is the number of units of analysis.

3.3 Spatial autocorrelation

The identification of a spatial pattern in the differences between homologous accessibilities is based on the Global Moran's Index (*I*), which aims to assess the interdependence between the values observed for a variable in a given unit of analysis and in its neighbors through the covariance between them (BLACK, 1992;

LUZARDO; CASTAÑEDA FILHO; RUBIM, 2017). In a univariate analysis, that is, when one aims to evaluate the autocorrelation of a variable between a given polygon and those close to it, the calculation of *I* can be performed as presented by Eq. (5), with values ranging from -1 to 1. Values less than zero indicate negative spatial autocorrelation; and greater than zero, positive (MORAN, 1947). Furthermore, clusters of positive spatial association and outliers of negative spatial association can be identified through Local Indicators of Spatial Association (LISA), that is, by means of the Local Moran's Index, as shown in Eq. (6) (ANSELIN, 1995).

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij} \times (x_i - \bar{x}) \times (x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{5}$$

$$LISA_i = \frac{(x_i - \bar{x})}{m} \times \sum_{j=1}^{n} w_{ij} \times (x_j - \bar{x}) \tag{6}$$

where *I* is the Global Moran's Index; $LISA_i$ is the Local Moran's Index of zone *i*; *n* is the number of units of analysis; w_{ij} is equal to 1 if zone *i* is contiguous to zone *j*, and 0 otherwise; x_i and x_j are, respectively, the values of the analysis variable *x* for zones *i* and *j*; $\bar{x}$ is the mean of *x*; and *m* is the variance of *x*.

In this study, spatial analyses were carried out using the GeoDa software, available for free and which, unlike other similar software, allows the user to also conduct bivariate analyses, that is, verifying the spatial dependence of a variable observed in a unit of analysis with another variable observed in adjacent units, and the mathematical formulation for this is simply adapted from the one presented here (the expression (x_j - $\bar{x}$) is replaced by elements referring to the second variable of interest).

4 RESULTS AND DISCUSSION

The results and discussions of the research will be presented in this section.

4.1 Comparing shortest homologous routes

The shortest routes were calculated using both sources of altimetric information for the studied area and then compared. Altogether, for each of the 475 units of analysis, 950 shortest routes were identified to access the georeferenced TAs, resulting in 451,250 pairs of homologous routes, among which only 9,789 (2.17%) correspond to an identical route.

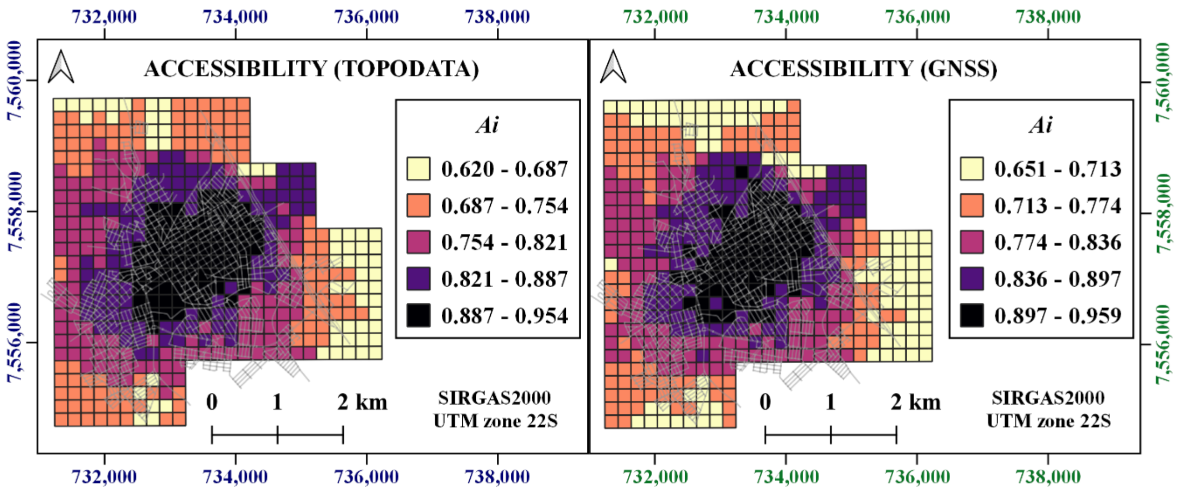
In practical terms, no significant differences were observed between travel times for the homologous routes, and those calculated using GNSS data were, on average, only 7 seconds faster than their peers, in addition to 448,708 (99.43%) calculated homologous routes diverging by less than 1 minute from each other. However, some cases were identified in which the difference between the travel times to access the same bicycle TA, from the same origin, is around 2 minutes, particularly with origins in the extreme southeast of the study area, and with a destination in the central region. Regarding travel distances, in relative percentage terms, the results also indicate that correlated routes are systematically similar to each other, differing, on average, by 1.7%, although extreme cases are observed in which this difference is 70%.

4.2 Comparing TOPODATA and GNSS accessibilities

Figure 2 presents comparative maps of cyclists' accessibility to TAs in the city of Bariri-SP, measured based on the TOPODATA DEM and GNSS data. Visually, there is a clear similarity between them, in which the central region of the city, where most of the TAs are concentrated, is characterized by high levels of accessibility; and peripheral regions, for which travel times to these destinations are considerably longer, are characterized by lower levels of accessibility.

Table 3 presents descriptive statistics for the TOPODATA and GNSS accessibilities, as well as for the differences between their homologous values ($\Delta_i = A_{i,GNSS} - A_{i,TOPODATA}$). Regarding TOPODATA accessibility, the values for the study area vary between 0.620 and 0.954; and GNSS accessibility, between 0.651 and 0.959. The mean difference between homologous accessibilities suggests that, when used for cycling planning purposes, the TOPODATA DEM reflects values approximately 0.4% lower than those measured by field data, ranging from -2.4% to 6, 6% for some units of analysis.

Figure 2 – Accessibility to bicycle TAs in the city of Bariri-SP.



Source: Authors (2022).

Table 3 – Descriptive statistics: TOPODATA accessibility, GNSS accessibility and Δ between them.

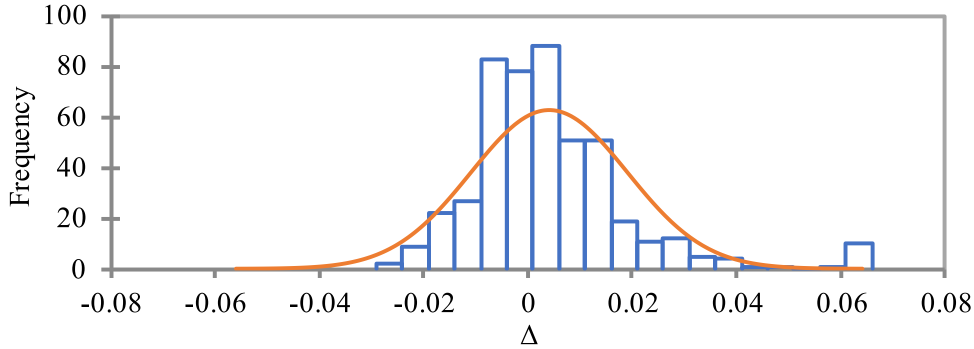
Descriptive statistics	A_i (TOPODATA)	A_i (GNSS)	Δ
Mean	0.793	0.797	0.004
Standard deviation	0.082	0.082	0.015
Variance	0.007	0.007	0.000
Median	0.792	0.797	0.002
Mode	0.744	0.738	-0.006
Skewness	0.031	0.079	1.647
Kurtosis	-0.930	-1.113	4.491
Maximum	0.954	0.959	0.066
Minimum	0.620	0.651	-0.024
n	475	475	475

Source: Authors (2022).

In order to compare the homologous accessibility samples, the differences between them were previously submitted to normality tests, to later select the most appropriate statistical test, that is, the paired samples *t*-test for affirmative cases, and equivalent non-parametric tests otherwise (FIELD, 2009). Both the Shapiro-Wilk and D'Agostino-Pearson tests were performed using the free Real Statistics supplement for Microsoft Excel, and in none of them was the normal distribution of the sample verified, which can also be visually confirmed by the histogram shown in Figure 3. Thus, it was applied the two-tailed Wilcoxon signed-rank test for paired samples, whose results (*z-score* = 4.41; p = $1 \times 10^{-5} < 0.05$) suggest rejecting the null hypothesis that there is no difference between the medians of the TOPODATA (0.792) and GNSS (0.797) accessibility samples.

 DOI: http://dx.doi.org/10.14393/rbcv74n3-65117

Figure 3 – Frequency distribution of differences between homologous accessibilities.

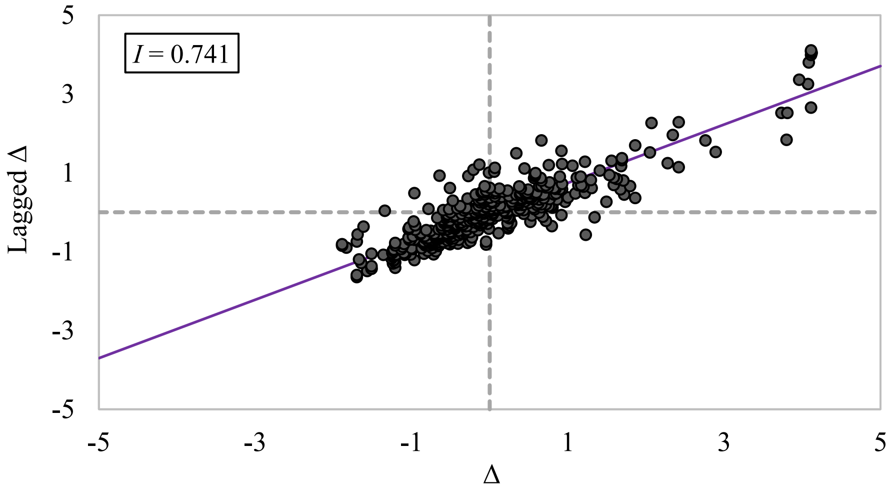


Source: Authors (2022).

4.3 Spatial autocorrelation between differences in homologous accessibilities

The Moran scatter plot is shown in Figure 4, which allows one to observe, as also suggested by the value of the Global Moran's Index ($I = 0.741$), a strong positive spatial autocorrelation between the differences in homologous accessibilities.

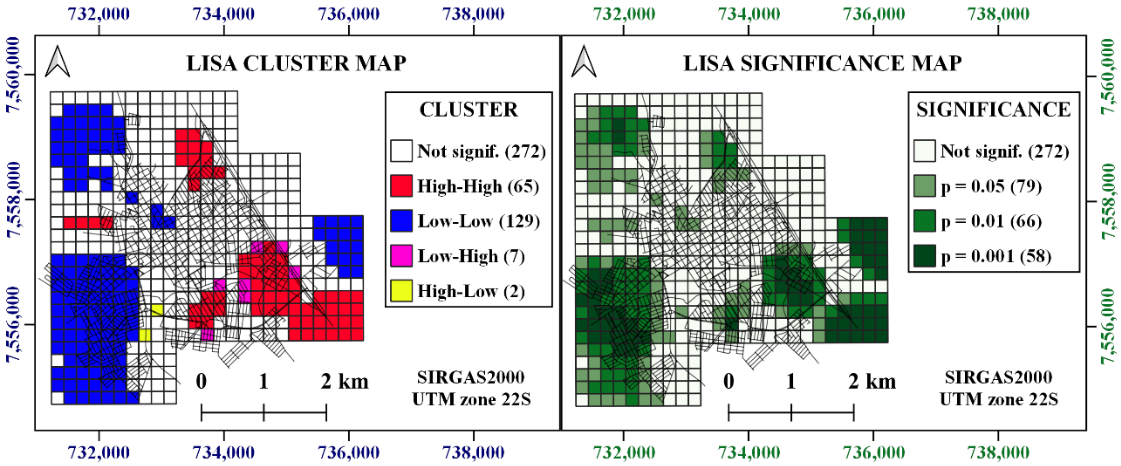
Figure 4 – Moran scatter plot.



Source: Authors (2022).

Figure 5 presents the LISA cluster and significance maps. High-High clusters consist of census grid cells where there are significant positive differences between homologous accessibilities (i.e., where GNSS accessibility is greater than TOPODATA accessibility, close to other cells characterized by the same phenomenon), which are concentrated mainly in the extreme southeast of the study area, although some of them can also be observed on a smaller scale in other regions distant from the city center. On the other hand, Low-Low clusters, which suggest positive spatial association between units of analysis where TOPODATA accessibility is greater than GNSS accessibility, are identified on a larger scale in the southwest region of the study area, but smaller clusters are also observed in the northwest and southeast regions of the city. In only 9 grid cells were outliers observed regarding the differences between homologous accessibilities, that is, 7 cells in which TOPODATA accessibility is greater than GNSS accessibility, contiguous to others where the opposite phenomenon is observed (Low-High); and 2 cells where GNSS accessibility is greater than TOPODATA accessibility, close to others where TOPODATA accessibility is overestimated (High-Low).

Figure 5 – Spatial autocorrelation between differences in homologous accessibilities.

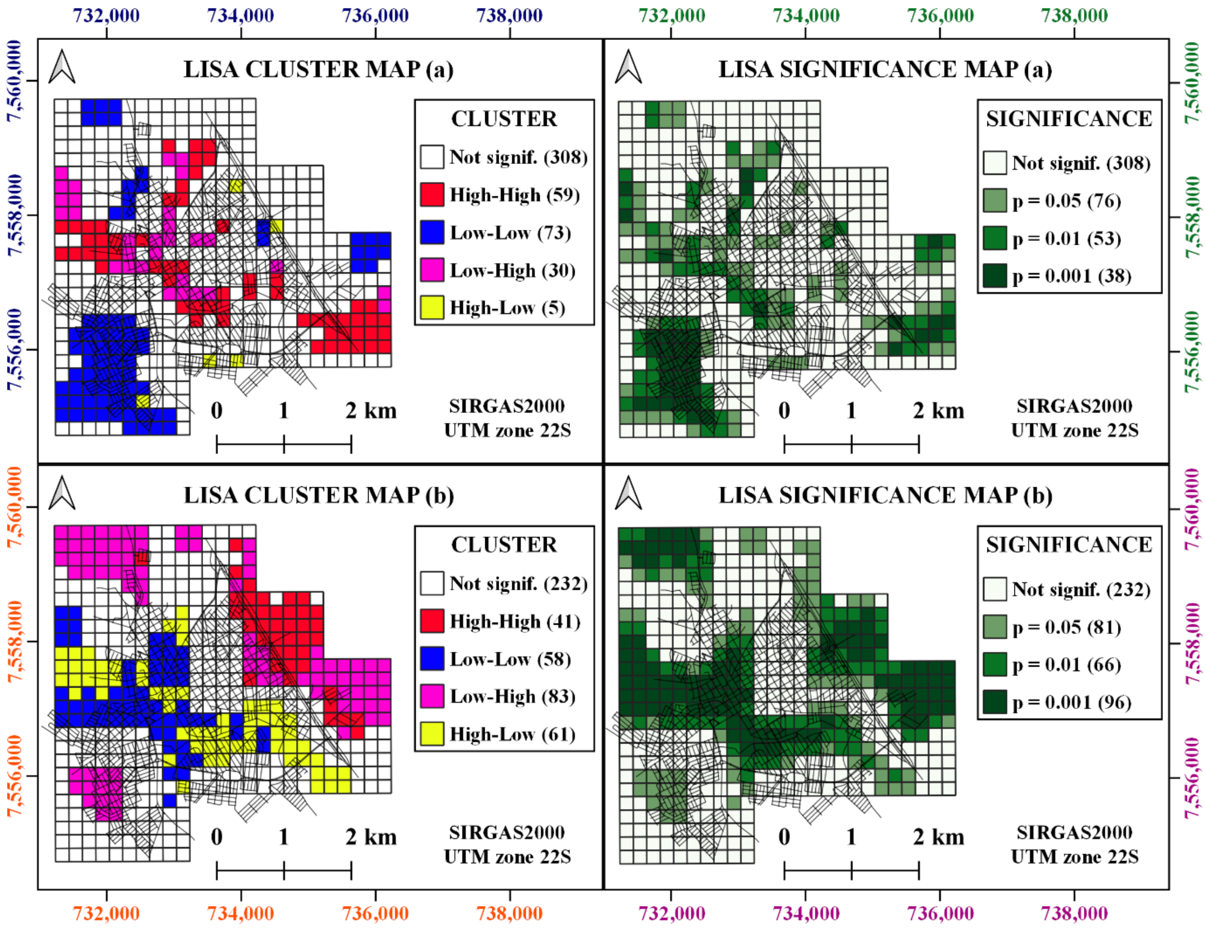


Source: Authors (2022).

4.3.1 BIVARIATE SPATIAL ANALYSES

Aiming to investigate possible reasons for the strong positive autocorrelation of the previously evaluated variable, two other bivariate analyses were performed. The results are shown in Figure 6.

Figure 6 – Bivariate analyses between the differences in homologous accessibilities and (a) TOPODATA average slopes and (b) TOPODATA average altitudes of the units of analysis.



Source: Authors (2022).

In the first analysis, from the generation of a TOPODATA slope map derived from the original raster map, the spatial dependence between the differences in homologous accessibilities and the average

TOPODATA slopes of adjacent cells was evaluated. In the second, this spatial dependence was evaluated in terms of the TOPODATA average altitudes of these immediate neighbors. To calculate the average values, in both cases, the QGIS RasterStats plugin was used.

Regarding the first analysis, the value of the Global Moran's Index (I = 0.270) indicates that there is a moderate to weak positive spatial dependence between the variables analyzed. Regarding local indicators, High-High clusters are observed in several regions of the study area, especially in the extreme southeast and in the northwest and central regions, which consist of cells of the census grid where TOPODATA accessibility is underestimated, close to cells characterized by steep TOPODATA average slopes. Low-Low clusters are mostly found in the flatter southwest region of Bariri-SP, where TOPODATA accessibility is overestimated. Altogether, 35 outliers were identified from this first bivariate analysis, 30 of which were grouped as Low-High and 5 as High-Low.

Regarding the second analysis, the value of the Global Moran's Index (I = -0.217) also indicates that there is a moderate to weak spatial dependence between the analysis variables, however, negative. In terms of local indicators, High-High clusters are mostly observed in the northeast region of the study area, which consist of units of analysis where TOPODATA accessibility is underestimated, close to cells with high average altitudes of the DEM. Low-Low clusters, for which TOPODATA accessibility is overestimated, are identified in the central region of the city, characterized by the lowest local altitudes (the reader should refer to Figure 1). In total, 144 outliers from this second bivariate analysis were identified, 83 of which were grouped as Low-High and 61 as High-Low, in the latter case, also predominant in the central region, consisting of grid cells close to lower regions and in which GNSS accessibility is greater than TOPODATA accessibility.

4.4 Overall accessibility of the population to bicycle TAs

Table 4 presents values regarding the overall accessibility of different population groups to bicycle TAs in the city of Bariri-SP, that is, weightings of the accessibility in each unit of analysis by their respective resident populations belonging to different age or monthly income groups.

Table 4 – Overall accessibility of different population groups to bicycle TAs in the city of Bariri-SP.

Age or income group	TOPODATA accessibility	GNSS accessibility
10 to 29 years old	0.853	0.855
30 to 49 years old	0.858	0.860
50 to 69 years old	0.868	0.870
70 years or older	0.883	0.885
≤ 2 minimum wages	0.856	0.857
2 to 5 minimum wages	0.874	0.877
> 5 minimum wages	0.894	0.898

Source: Authors (2022).

Pragmatically speaking, corresponding values of TOPODATA and GNSS accessibilities are quite similar to each other, and for all population groups evaluated, an overall accessibility to bicycle TAs greater than 85% was observed, regardless of the source of altimetric information used. Specifically with regard to the age of cyclists, according to Sousa (2012), the cycling demand in Brazil mostly comprises individuals of an economically active age. In this context, it can be observed that the age group with the greatest ease of access to TAs in the city of Bariri-SP is precisely the one that refers to individuals with less potential to use a bicycle, that is, aged 70 years or older.

Similar results were also found in relation to income. In small Brazilian cities, that is, cities whose population is limited to 100 thousand inhabitants (IBGE, 2016), as in the case of Bariri-SP, it is estimated that two-thirds of all cyclists have a monthly income of up to 2 minimum wages (SOARES; GUTH, 2018). On the other hand, it is noted that, at the study site, the overall accessibility (TOPODATA or GNSS) of this population group is precisely the lowest among all the income groups evaluated. The highest, in turn, is observed for more economically favored individuals, i.e., whose monthly income is greater than 5 minimum wages, who have greater purchasing power to enjoy individual motorized transport and, consequently, have less potential to use a bicycle in daily trips.

It is important to highlight that these results, by suggesting a certain inequity of access to bicycle TAs in the city of Bariri-SP, are subject to uncertainties, as the use of the same decay function of the gravitational accessibility measure indistinctly for the entire population may under- or overestimate the predisposition of some population group to cycling, often valuing the overall accessibility of wealthier individuals who tend to reside in the central region (GIANNOTTI; TOMASIELLO; BITTENCOURT, 2022), precisely the one with the highest concentration of TAs.

5 FINAL CONSIDERATIONS

This study aimed to evaluate the usability of the TOPODATA DEM to measure the accessibility of cyclists to bicycle TAs, seeking to discuss the possible inclusion of this open data as technical support to develop cycling projects and mobility plans. A case study was conducted in a small Brazilian town in inland São Paulo state, Bariri-SP, for which previous topographic surveys were available, making it possible to compare the results obtained from both sources of information.

The results of the case study suggest shortest homologous routes similar to each other, although the paired samples of TOPODATA and GNSS accessibilities differ statistically. A strong spatial autocorrelation of this difference was observed. Bivariate analyses indicate a moderate to weak positive spatial dependence between this variable and the TOPODATA slopes; and negative from moderate to weak regarding the model altitudes. The overall accessibility to bicycle TAs in the city of Bariri-SP, regardless of the population group evaluated, is similar for both altimetric data used.

Regarding the limitations of the research, it should be mentioned that the census data used refer to the context of more than a decade ago, as the 2020 Demographic Census had to be postponed due to the Coronavirus pandemic. Regarding future work, we recommend reproducing the method using other more up-to-date, relevant and higher spatial resolution DEMs, as well as in larger municipalities or those characterized by hilly terrain.

Acknowledgements

This study was financed by the Coordination for the Improvement of Higher Education Personnel (CAPES-Brazil, Process 88887.475432/2020-00) - Finance Code 001.

Authors' contributions

The first author, Marcelo Monari, was responsible for developing the research methodology, formally analyzing the results, writing and editing the article. Both the second and third authors, in that order, Paulo Cesar Lima Segantine and Irineu da Silva, were also responsible for developing the methodology, in addition to supervising and revising the text of the article.

Conflict of interest

The authors declare that there is no conflict of interest.

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