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Evaluating the TOPODATA digital elevation model as a source of information for cycling planning purposes: a case study for a small-sized Brazilian city

Avaliação do MDE TOPODATA como fonte de informação para fins de planejamento cicloviário: um estudo de caso para uma cidade brasileira de pequeno porte

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ABSTRACT
The present study aims to evaluate the TOPODATA Digital Elevation Model (DEM) as a source of relevant altimetric information for urban cycling planning. A case study was conducted in the city of Bariri-SP. The Cartographic Accuracy Standard of Digital Cartographic Products (PEC-PCD), assessed by comparing the TOPODATA altitudes with homologous altitudes surveyed by a precise satellite method (GNSS), suggests that the DEM may not be adequate for phases of cycling planning that require greater detailing of the elements to be designed. A moderate to strong positive spatial autocorrelation was observed between the DEM errors. Regarding its usability for estimating the average slopes of the road segments, however, the results suggest that TOPODATA average slopes do not differ statistically from those estimated with field-surveyed data and, for the two criteria adopted for acceptable gradient lengths for cycling, more than 82% of the road segments were classified similarly using both sources of information.

RESUMO
O presente trabalho busca avaliar o Modelo Digital de Elevação (MDE) TOPODATA como fonte de informações altimétricas relevantes ao planejamento cicloviário urbano. Um estudo de caso foi conduzido em Bariri-SP. O Padrão de Exatidão Cartográfica dos Produtos Cartográficos Digitais (PEC-PCD), avaliado comparando-se altitudes TOPODATA com altitudes homólogas levantadas em campo por método preciso satelital (GNSS), sugere que o MDE pode não ser adequado às fases do planejamento cicloviário que requerem um maior detalhamento dos elementos a serem projetados. Uma moderada a forte autocorrelação espacial positiva foi observada entre os erros do MDE. Com relação à sua usabilidade para se estimar declividades médias de segmentos viários, no entanto, os resultados sugerem que as declividades médias TOPODATA não diferem estatisticamente daquelas estimadas com dados de campo e, para os dois critérios adotados de rampas aceitáveis ao ciclismo, mais de 82% dos segmentos viários foram igualmente avaliados por ambas as fontes de informação.

1. INTRODUCTION

The current need to promote sustainable urban mobility has required transportation planners to propose solutions that can meet human needs for safe and ecologically correct daily trips. In Brazil, devising urban mobility plans in municipalities with a population of more than

20,000 inhabitants (with an emphasis on public and active transportation modes) has become a legal requirement for more than a decade (Brazil, 2012). However, most Brazilian municipalities, especially small and medium-sized ones, lack basic information necessary for this purpose, such as origin-destination surveys, traffic studies, road accident georeferencing and local topographic surveys.

Bicycle use, in addition to factors related to the cyclists themselves (gender, age and income), is influenced by a set of factors related to the route, such as distance or travel time (Hood *et al*., 2011; Broach *et al*., 2012), cycling infrastructure (Stinson and Bath, 2003; Sener *et al*., 2009; Larsen and El-Geneidy, 2011), and pavement conditions (Antonakos, 1994; Kang and Fricker, 2013), among others.

Terrain slope is also an influencing factor in bicycle commuting (Menghini *et al*., 2010; Winters *et al*., 2010), as steep up-slopes demand great physical effort by the cyclists, and steep down-slopes make it difficult to maintain balance. Thus, whenever possible, it is recommended that cycling routes be designed with slopes limited to 3%, with values of up to 5% still tolerable by most cyclists; otherwise, steeper road segments should be evaluated according to their respective gradient lengths acceptable for cycling (AASHTO, 1999; AUSTROADS, 2014). However, accurate representations of the Earth's ground surface from aerophotogrammetric, laser scanning or levelling surveys are rarely available, requiring transportation planners to benefit from openly available Digital Elevation Models (DEM) (Ziemke *et al*., 2017; Masri and Bigazzi, 2019).

The cycling potential of a city or region is often evaluated in terms of slopes suitable for cycling, and unreliable terrain representations can limit the cycling network. Winters *et al*. (2013) relied on the maximum slope (extracted from a DEM with a spatial resolution of 30 meters) between a unit of analysis and its neighbors to measure the cycling potential of Vancouver (Canada). Krenn *et al*. (2015) mapped the cycling potential of Graz (Austria) based on the average slopes within a 200-meter buffer from each unit of analysis. Ma and Dill (2017) calculated the percentage of area with slopes steeper than 25% within a 1-mile network buffer to assess the cycling potential of units of analysis in Portland (USA). Lin and Wei (2018) measured the relative cycling potential between the traffic zones in the Daan district of Taipei (Taiwan), with the worst-rated zones being those affected by the hilly terrain. In Brazil, Neri (2012) assessed the cycling potential of the city of Maringá through the percentage of the study area with a slope of less than 5%.

Bicycle routing applications also often benefit from DEM. Payne and Dror (2015) developed an algorithm to compose a topographical road graph, so that the cycling routes could be identified to minimize perceived effort for cyclists of different levels of expertise. In Brazil, Magalhães *et al.* (2015) sought to define a cycling network in the medium-sized city of Montes Claros through a multi-criteria analysis regarding the Bicycle Level of Service and the slope of the road segments. In the latter case, the altimetric information was obtained from the Google Earth platform based on the Shuttle Radar Topography Mission (SRTM) DEM.

The SRTM was a space mission carried out in February 2000 by 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), whose objective was to produce an Earth high-resolution DEM through interferometry technology, that is, the acquisition of altimetric data by means of two Synthetic Aperture Radar (SAR) antennas separated by a 60-meter extender device (Farr *et al.*, 2007). The survey covered about 80% of the Earth's terrain, from latitude 56°S to 60°N. Herein, the data referring to South America, which was originally made available with a near 90-meter spatial resolution, was later reprocessed along the Brazilian territory by the Brazilian National Institute for Space Research (INPE-Brazil), in a project entitled TOPODATA, so that they could achieve a 30-meter spatial resolution (Valeriano and Rossetti, 2012). In this context, although TOPODATA DEM maintains the geomorphological properties of the original model with higher spatial resolution, the logical consistency, completeness, positional and temporal accuracy and usability (IBGE, 2017) of the spatial data extracted from it must still be assessed.

The absolute altimetric positional accuracy of these data can be assessed through statistical indicators resulting from the comparison between the DEM altitudes and the homologous altitudes surveyed in the field, suggesting the minimum map scales for which the DEM reflects reliable results (Landau and Guimarães, 2011; Garofalo and Leisenberg, 2015). Simeão *et al.* (2019), for example, sought to evaluate the cycling network of the city of São Paulo (Brazil) using two different strategies, i.e., extracting information directly from a slope map at a scale of 1:100,000 (available in the city's database), and producing a DEM from a 5-meter contour map at 1:1,000 scale. The results suggest divergences regarding the percentages of the city's cycling network suitable for cycling due to the different map scales of the cartographic products.

Despite the obvious importance of establishing a level of conformity of the digital cartographic products with the real world, the isolated analysis of the positional accuracy of a given DEM is not always sufficient for the professionals who use Geographic Information Systems (GIS), from which *raster* data geoprocessing can benefit from any map scale. Therefore, a complementary analysis of the usability of this DEM must be carried out, allowing GIS users to verify whether or not it meets the specifications of a particular application of interest (Araújo, 2016).

The present study aims to evaluate the TOPODATA DEM as a source of relevant altimetric information for urban cycling planning. A case study was conducted for an area of 7 km^2 within the urban limits of Bariri, a small-sized Brazilian city located in inland São Paulo state. To achieve this goal, the following research questions must be answered:

1) What is the altimetric positional quality of the TOPODATA DEM when assessed through the current Brazilian standards? How relevant is it to cycling planning?
2) Does the error propagation of the TOPODATA DEM follow a spatial pattern?
3) Can cycling planning benefit from TOPODATA DEM to assess road segments suitable for cycling according to different criteria?

2. METHOD

This section presents the research method. Spatial data geoprocessing benefited from QGIS 3.8.2, and statistical analyses were performed using the Real Statistics Resource Pack for Microsoft Excel.

2.1. Cartographic Accuracy Standard of Digital Cartographic Products (PEC-PCD)

In Brazil, as defined by Decree Nr. 89,817 of June 20, 1984 (Brazil, 1984), the assessment of the positional quality of the information extracted from the cartographic products should benefit from a statistical indicator called Cartographic Accuracy Standard (or PEC, which in Portuguese stands for *Padrão de Exatidão Cartográfica*). However, due to the constant evolution of spatial data acquisition instruments and digital processing, the Brazilian Directorate of the Geographical Service (DSG-Brazil) has required, since 2015, that such an assessment be based on the Cartographic Accuracy Standard of Digital Cartographic Products (PEC-PCD), updating the original guidelines designed for the analogue products (Carvalho and Silva, 2018).

Regarding the altimetric positional quality, the PEC-PCD criterion subdivides the cartographic products into four classes (A, B, C and D). For a DEM, at a given map scale, to assume one of these classes, it is necessary to compare the altimetric coordinates extracted from a sample of DEM points with the altimetric coordinates of homologous points surveyed in the field, requiring that 90% or more of the observed errors are lower than the admissible limits shown in Table 1. In addition, the Root Mean Square Error (RMSE) of the evaluated sample, calculated through Equation 1, must be compared with the maximum Standard Error (SE) required for each class, which are also shown in Table 1 and are adopted according to the most convenient vertical spacing between contour lines at each map scale (Ferreira, 2014; Viel *et al.*, 2020). This methodology, however, is only valid when the studied variable is normally distributed, since the PEC-PCD, considering a probability interval of 90% around the mean, is equal to 1.6449 times the SE (Carvalho and Silva, 2018).

Table 1 – PEC-PCD altimetric positional quality classes (Source: DSG, 2011)

Class	**Map scale**															
	1:1,000 (Eq.*=1 m)		1:2,000 (Eq.*=1 m)		1:5,000 (Eq.*=2 m)		1:10,000 (Eq.*=5 m)		1:25,000 (Eq.*=10 m)		1:50,000 (Eq.*=20 m)		1:100,000 (Eq.*=50 m)		1:250,000 (Eq.*=100 m)	
	PEC (m)	SE (m)	PEC (m)	SE (m)	PEC (m)	SE (m)	PEC (m)	SE (m)	PEC (m)	SE (m)	PEC (m)	SE (m)	PEC (m)	SE (m)	PEC (m)	SE (m)
A	0.27	0.17	0.27	0.17	0.54	0.34	1.35	0.84	2.70	1.67	5.50	3.33	13.70	8.33	27.00	16.67
B	0.50	0.33	0.50	0.33	1.00	0.66	2.50	1.67	5.00	3.33	10.00	6.66	25.00	16.66	50.00	33.33
C	0.60	0.40	0.60	0.40	1.20	0.80	3.00	2.00	6.00	4.00	12.00	8.00	30.00	20.00	60.00	40.00
D	0.75	0.50	0.75	0.50	1.50	1.00	3.75	2.50	7.50	5.00	15.00	10.00	37.50	25.00	75.00	50.00

*Eq.: vertical spacing (equidistance) between contour lines.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(H_{DEM_i} - H_{control_i})^2}{n}} \tag{1}$$

where, H_{DEM_i} is the DEM altitude of the point *i*; $H_{control_i}$ is the control altitude of the point *i*; and n is the sample size.

To present itself as a technical subsidy for the different phases of cycling planning, the DEM must assume class A for the following map scales: 1:50,000 and 1:10,000 or greater. The 1:50,000 map scale is often used for the development of Bicycle Master Plans, which involve proposing projects at the municipal level. Thus, physical barriers must be identified to assess the technical-financial feasibility and ease of implementation of such projects. Map scales of 1:10,000 or greater, meanwhile, are often used for small-area and corridor-level planning, which involves promoting bicycle access along and across roads, selecting the appropriate cycling infrastructure, etc., as well as cost-benefit analysis, which requires more detailed information about the terrain to budget earthwork costs (Robbi, 2000; Toole, 2010).

2.1.1. Control points

The coordinates of the control points (Figure 1) were surveyed from September 7 to 22, 2017, through the GNSS Post-Processed Kinematic (PPK) relative positioning, which was performed across the road system of the study area. Two dual-frequency GNSS receivers were used in the field survey.

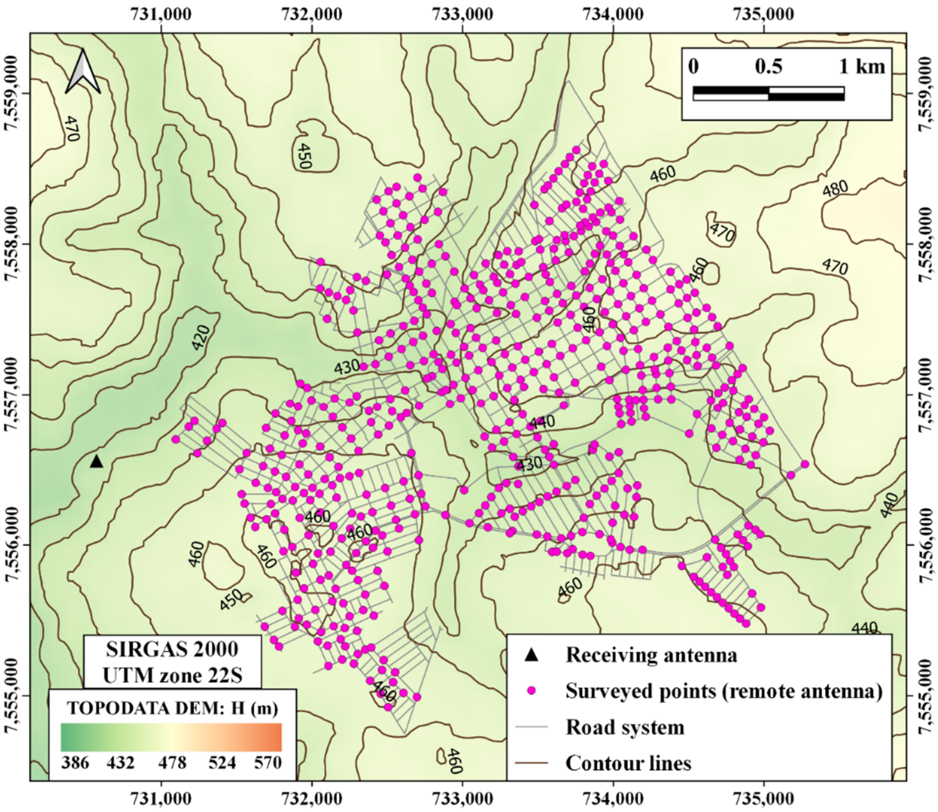

Figure 1. Surveyed control points (GNSS) and TOPODATA DEM for the city of Bariri, SP

In short, a static GNSS receiving antenna taken as a reference was positioned at a base station outside the urban limits of the city of Bariri-SP so that GNSS data could be collected uninterruptedly for almost 9 hours. The base station coordinates were obtained by baseline adjustment from 3 different active stations of the Brazilian Network for Continuous Monitoring (RBMC-Brazil). Then, the GNSS relative kinematic positioning measurements were carried out by means of simultaneous satellite tracking (1 second tracking rate) at the base station and on moving remote points positioned on the roof of a vehicle driven on the road segments within the study area. Finally, the coordinates of these remote points were computed by means of the data post-processing, using the LEICA Geo Office Combined V7.0 software with its standard configuration (Silva and Segantine, 2015; Monari, 2018).

The field survey allowed the positioning of thousands of points within the study area, among which all those points for which the ambiguity (integer number of signal cycles between receiver and satellite) could not be determined (float solution) were discarded. The geometric heights referenced on the Earth's ellipsoidal surface were converted into orthometric altitudes by subtracting their respective geoid undulations obtained by batch processing in the MAPGEO2015 software, an accurate geoid model for the Brazilian territory. Then, by using georeferenced OpenStreetMap (OSM) vector layers, which are representative of the local road system, a selection of points within a 5-meter buffer from each network node was performed. In cases where the same buffer included several points, only those closest to their respective nodes were selected, resulting in a final sample of 568 control points.

Figure 1 also presents the TOPODATA DEM for the city of Bariri-SP. According to the classification proposed by the Brazilian Agricultural Research Corporation (EMBRAPA, 1979), about 62% of the study area consists of flat terrain (slopes of less than 3%), 37% consists of smoothly undulating terrain (slopes between 3 and 8%), and the remaining 1% consists of moderately undulating terrain (slopes between 8 and 13%).

2.1.2. D'Agostino-Pearson Omnibus Test

To verify whether or not the differences between the homologous altitudes are normally distributed, due to the sample size (n > 50), the D'Agostino-Pearson Omnibus Test was performed, which allows identifying deviations from normality based on both the skewness and the kurtosis statistics, as presented by Equations 2 to 5. The K^2 statistic follows a chi-square distribution with two degrees of freedom when the population is normally distributed (D'Agostino and Pearson, 1973).

$$K^2 = Z^2\left(\sqrt{b_1}\right) + Z^2(b_2) \tag{2}$$

$$\sqrt{b_1} = \frac{m_3}{(m_2)^{\frac{3}{2}}} \tag{3}$$

$$b_2 = \frac{m_4}{(m_2)^2} \tag{4}$$

$$m_k = \frac{1}{n} * \sum_{i=1}^{n} (x_i - \bar{x})^k \tag{5}$$

where, $Z\left(\sqrt{b_1}\right)$ and $Z(b_2)$ are the normal approximations to skewness $(\sqrt{b_1})$ and kurtosis (b_2) statistics, respectively; m_k is the k-th sample moment; $\bar{x}$ is the sample mean; and n is the sample size.

2.1.3. Moran's Index (I)

The spatial autocorrelation between DEM errors was evaluated by the Global Moran's Index (*I*), whose values between 0 and +1 indicate positive spatial autocorrelation, and between 0 and -1 indicate negative (Moran, 1947). In turn, the Local Moran's Index was used to evaluate the relationship between a given sample point and its neighbors, signaling homogeneity or diversity of data through the covariance between them (Luzardo *et al.*, 2017). For both cases, the GeoDa software was used, which is available free of charge.

2.2. Average slopes of road segments

Graph theory was applied to the road system to define the intersections (nodes) and road segments (edges) of the study area. Regarding the movements allowed in the network, each road segment was assigned a single value corresponding to forward, reverse, or both flow directions, in a given column of the attributes table. Then, a joint analysis of the flow direction and the altitudes of the start and end nodes of each link in the network made it possible to identify the up-slope and down-slope road segments, as well as those that should be evaluated for both situations. Although many cyclists do not travel according to the flow direction allowed on the roads, the Brazilian Traffic Code (CTB, 2010) emphasizes that, in the absence of cycling infrastructure (as in the case study), that is, in mixed traffic situations, cycling should take precedence over the motorized traffic, as long as it complies with the regulated flow directions. In this context, in addition to the PEC-PCD already described, the homologous average slopes of the road segments (Equation 6) calculated both by the DEM and by the altimetric coordinates surveyed in the field were also compared. This analysis, however, was restricted to only 1,141 local road segments whose start and end nodes belong to the sample control points described in the previous sections.

$$i_e(\%) = \frac{H_{v_e} - H_{u_e}}{L_e} \times 100 \qquad (2)$$

where, H_{u_e} and H_{v_e} are the altitudes of the start (u) and end (v) nodes of the road segment e, respectively; and L_e is the length of the road segment e.

The average length of the evaluated road segments is approximately 86 meters. This is important information when considering the average slope of a given road segment, as it is assumed that no variations are observed in the topographic profile along the entire length assessed, which is less likely to occur the longer the road segment is. Thus, although the length range of the evaluated road segments varies from 3 to 648 meters, the descriptive statistics suggest only 30 sample outliers, which correspond precisely to the set of evaluated road segments longer than 200 meters.

The differences between the homologous average slopes were also subjected to normality tests. The normal distribution is a necessary assumption for performing parametric statistical tests, such as the paired samples *t*-test; otherwise, nonparametric equivalent tests must be performed, such as the Wilcoxon signed-rank test for paired samples, in the latter case, under the null hypothesis that the medians of the two samples are equal (Field, 2009; Rana and Suryanarayana, 2019).

2.2.1. Acceptable gradient lengths for cycling

Several criteria have been proposed since the 1970s (FHWA, 1977) regarding desirable and acceptable gradient lengths for cycling. Two of these criteria, proposed chronologically in the Guide for the Development of Bicycle Facilities (AASHTO, 1999) (Table 2) and in the Cycling Aspects of Austroads Guides (AUSTROADS, 2014) (Figure 2), are presented below.

Table 2 – Acceptable gradient lengths for cycling - Criterion 1 (Source: AASHTO, 1999)

Gradient (%)	Acceptable gradient length (m)
5 – 6	240
7	120
8	90
9	60
10	30
> 10	15

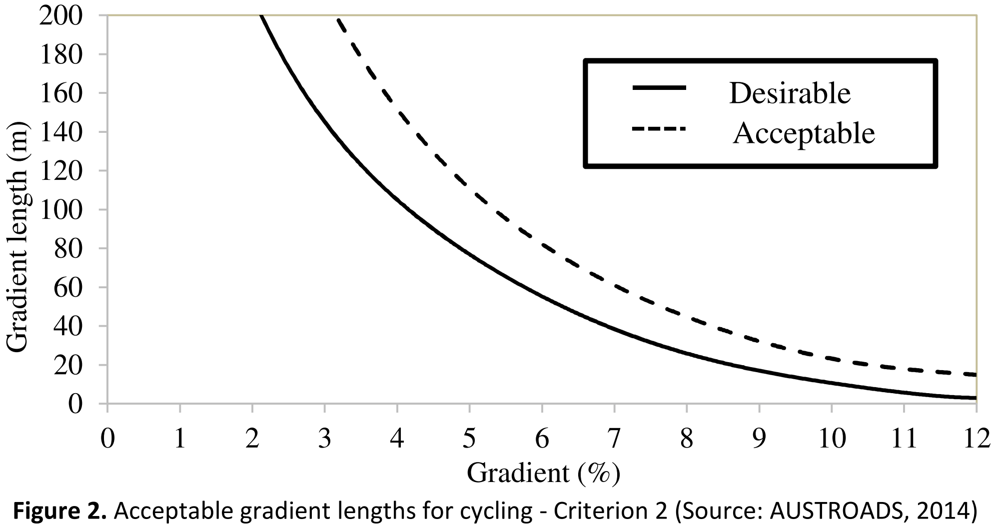

Figure 2. Acceptable gradient lengths for cycling - Criterion 2 (Source: AUSTROADS, 2014)

The two criteria were applied to the 1,141 previously selected road segments within the study area, seeking to compare their suitability for cycling using the average slopes estimated by both the TOPODATA DEM and the field data. In addition, a 5% slope threshold was adopted to consider down-slope road segments as suitable for cycling. For the two-way road segments, both situations (uphill and downhill) were evaluated separately, and those suitable for only one of them were considered "partially suitable for cycling".

3. RESULTS AND DISCUSSION

This section presents the results and discussion of the research.

3.1. PEC-PCD

Figure 3 presents the histogram of the differences between the homologous altitudes, whose mean, standard deviation and maximum and minimum values are 3.36, 2.75, 10.97 and -4.61 meters, respectively. The normality test based on both the skewness (0.042) and the kurtosis (0.585) of the sample suggests that the data do not significantly differ from the normal distribution (K^2 = 5.84; p = 0.054 > 0.05).

The sample of 568 evaluated points presented a RMSE of 4.34 meters. From this value and the percentages of observed errors lower than the admissible limits of the PEC-PCD methodology, as shown in Table 3, the altimetric positional quality classes A and B of the TOPODATA DEM are assumed for the map scales 1:100,000 and 1:50,000, respectively. However, the DEM does not suggest satisfactory altimetric positional quality for a map scale of 1:10,000 or greater.

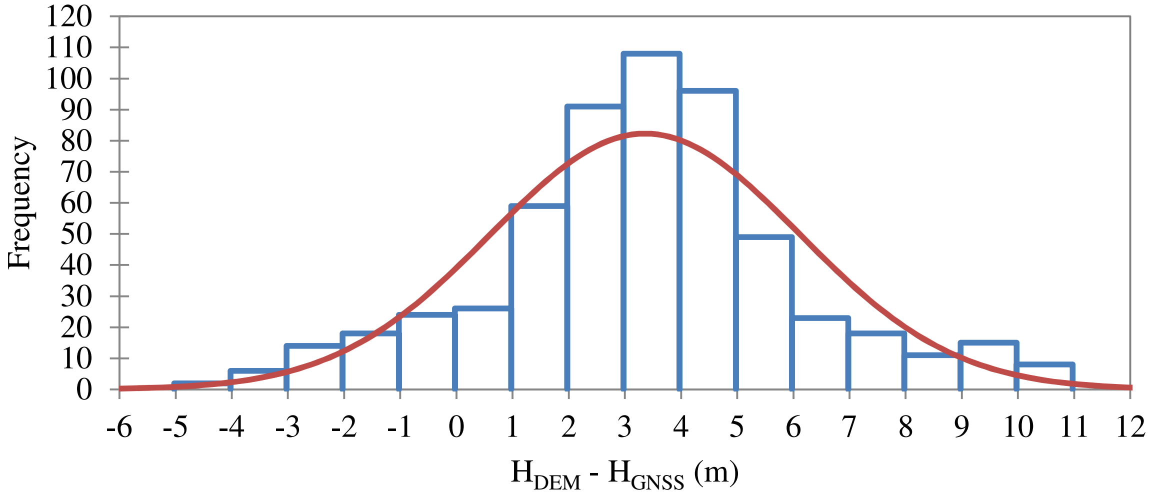

Figure 3. Histogram of the differences between the homologous altitudes

The interpretation of these results, specifically with regard to cycling, is that the use of TOPODATA DEM for phases of cycling planning that involve a greater detailing of the elements to be designed, such as small-area and corridor-level planning, may not be adequate, since the PEC-PCD suggests that the DEM does not present satisfactory altimetric positional quality for cadastral mapping scales, such as 1:5,000 or 1:10,000. At the municipal level, on the other hand, the DEM assumes class B for the map scale of 1:50,000, reflecting a similar quality to class A analogue products (PEC); therefore, presenting itself as an alternative to the vectorization of the existing topographic maps, such as those provided by the IBGE at this map scale, which are available only for a small percentage (14%) of the Brazilian territory (Silva *et al.*, 2018). This means that early stages of Bicycle Master Plan projects that do not require extensive terrain detail, such as feasibility studies and engineering sketches, can benefit from print-edited maps produced with TOPODATA DEM to identify any physical barriers for cycling and have their ease of implementation evaluated. At the regional level, whose topographical representation requires a map scale of 1:100,000 or smaller (for which the DEM assumes class A), feasibility studies of bolder projects, such as intercity cycle paths, could benefit from TOPODATA DEM.

Table 3 – TOPODATA DEM: altimetric positional quality classes

Map scale	Class							
	A		B		C		D	
	(%)	RMSE < SE	(%)	RMSE < SE	(%)	RMSE < SE	(%)	RMSE < SE
1:1,000	1.76	No	4.93	No	4.93	No	6.51	No
1:2,000	1.76	No	4.93	No	4.93	No	6.51	No
1:5,000	4.93	No	9.15	No	12.50	No	15.32	No
1:10,000	13.73	No	30.99	No	41.37	No	56.34	No
1:25,000	34.68	No	78.35	No	86.80	No	92.96	Yes
1:50,000	82.75	No	98.59	Yes	100	Yes	100	Yes
1:100,000	100	Yes	100	Yes	100	Yes	100	Yes
1:250,000	100	Yes	100	Yes	100	Yes	100	Yes

3.2. Spatial autocorrelation between DEM errors

Figures 4 and 5 show, in this order, the Moran scatter plot and the Local Indicators of Spatial Association (LISA) (Anselin, 1995) of the differences between the homologous altitudes. In the latter case, both the LISA cluster map and the LISA significance map are presented.

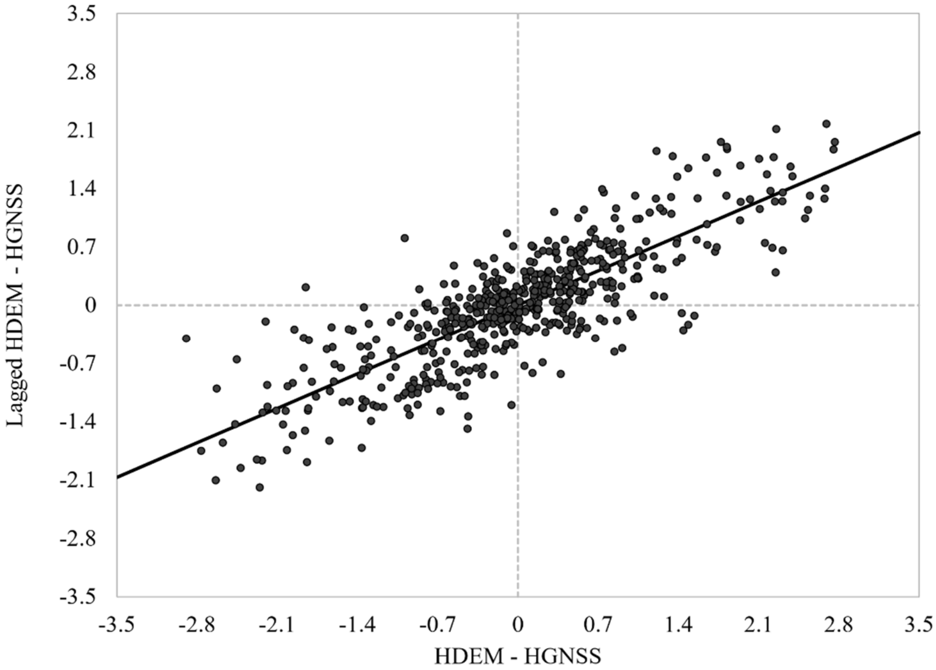

Figure 4. Moran scatter plot of the differences between the homologous altitudes

TOPODATA DEM altitudes are most overestimated in the central region of the study area. The Global Moran's Index (*I* = 0.591) suggests a moderate to strong positive spatial autocorrelation of the differences between the homologous altitudes. The LISA cluster map allows one to observe a slight tendency of error propagation along the streamlines, which corroborates the results of other studies in the literature with similar objectives (Holmes *et al.*, 2000). In addition, only 6 of the 568 points evaluated are considered sample outliers, with 3 grouped as "High-Low" and another 3 as "Low-High". In the latter case, it is observed that one refers to an elevated structure (bridge), as suggested by Masri and Bigazzi (2019).

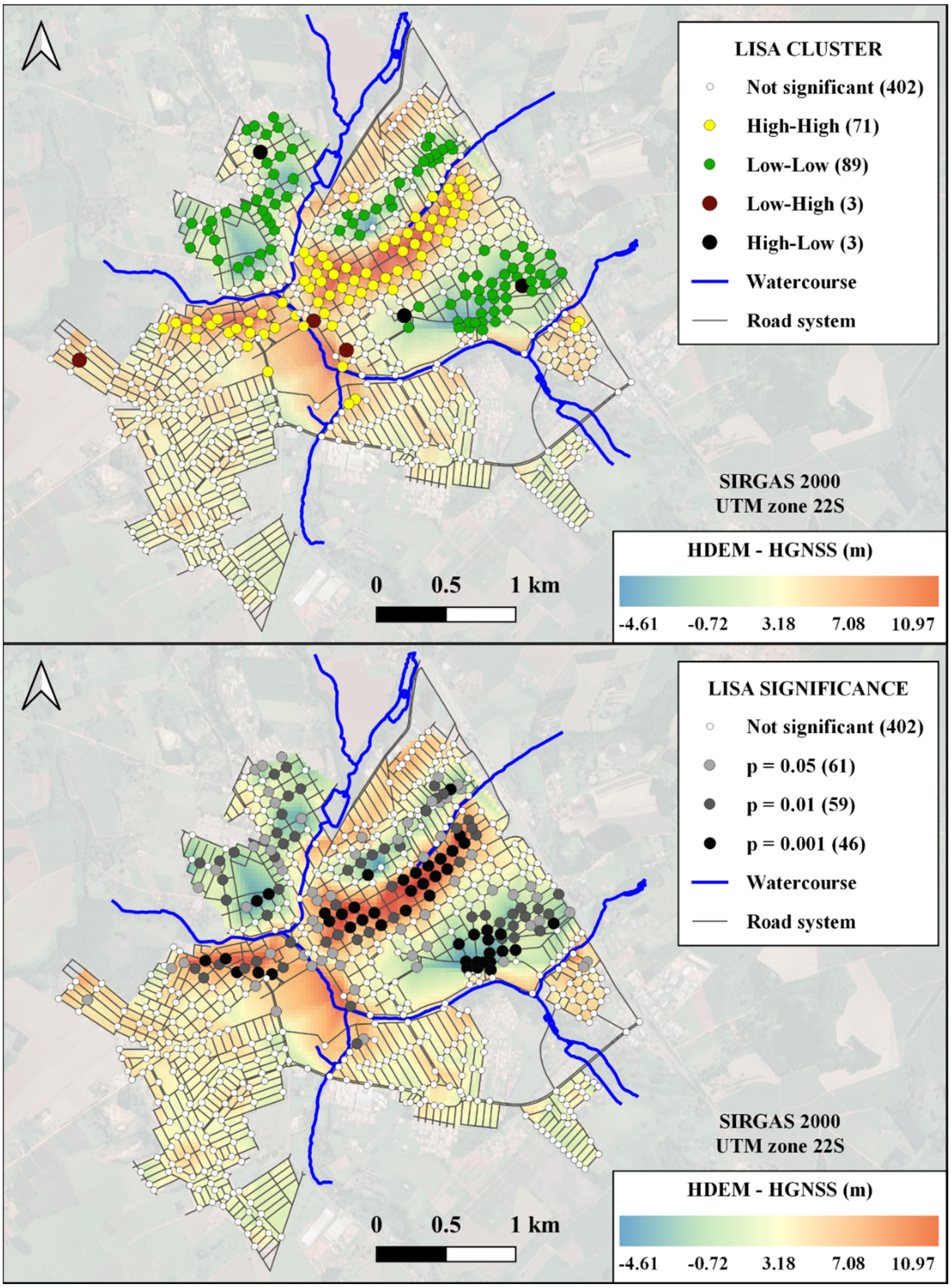

Figure 5. Spatial autocorrelation between differences in homologous altitudes

3.3. Suitability of road segments for cycling

Figure 6 presents the histogram of the differences between the homologous average slopes, whose mean, standard deviation and maximum and minimum values, in this order, are -0.04%, 1.96%, 7.86% and -7.88%. Unlike the differences between the homologous altitudes, the normality test based on both the skewness (-0.162) and the kurtosis (2.107) of the sample suggests that the differences between the homologous average slopes significantly differ from the normal distribution ($K^2 = 64.09$; $p = 1.21\times10^{-14} < 0.05$). Therefore, the two-tailed Wilcoxon signed-rank test for paired samples was applied ($z = 0.22$; $p = 0.83 > 0.05$), through which the null hypothesis was verified that there is no significant difference between the medians of these samples, i.e., the average slopes estimated using the TOPODATA DEM (1.66%) and GNSS data (1.83%).

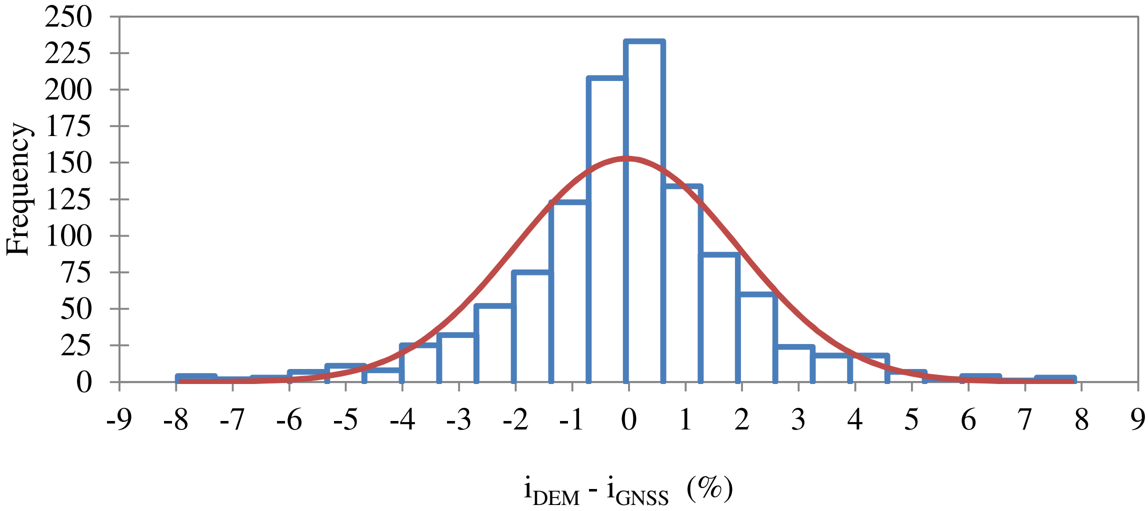

Figure 6. Histogram of the differences between the homologous average slopes

Regarding the suitability of road segments for cycling, the results are shown in Figure 7. Considering the two criteria proposed by the AASHTO (1999) and AUSTROADS (2014) guides, it is suggested that 1,012 and 949 of the road segments within the study area, respectively, are totally suitable for cycling when evaluated using the TOPODATA DEM; that 85 and 74 are only partially suitable; and that 44 and 118 are not suitable at all. Compared to each other, 1,021 road segments have the same classification regardless of the criterion adopted.

Analogously, considering the two criteria proposed by the AASHTO (1999) and AUSTROADS (2014) guides, it is suggested that 1,004 and 931 road segments within the study area, respectively, are totally suitable for cycling when evaluated using GNSS data; that 86 and 72 are only partially suitable; and that 51 and 138 are not suitable at all. When compared to each other, 1,007 road segments have the same classification regardless of the criterion adopted.

Finally, comparing both sources of altimetric information, 86.5% and 82.8% of the evaluated road segments have the same classification according to the AASHTO (1999) and AUSTROADS (2014) criteria, respectively. Furthermore, 25 and 59 road segments, in that same order, are strictly unsuitable for cycling according to their GNSS average slopes, but totally suitable according to their DEM average slopes; whereas 51 and 35 road segments are only partially suitable for cycling according to their GNSS average slopes, but totally suitable according to their DEM average slopes. It is also worth mentioning that the bridge whose end node was grouped as “Low-High” in the previous section is classified as totally suitable for cycling, by both criteria, when assessed through the TOPODATA DEM. However, it is considered not at all suitable for cycling, also by both criteria, when evaluated using GNSS data.

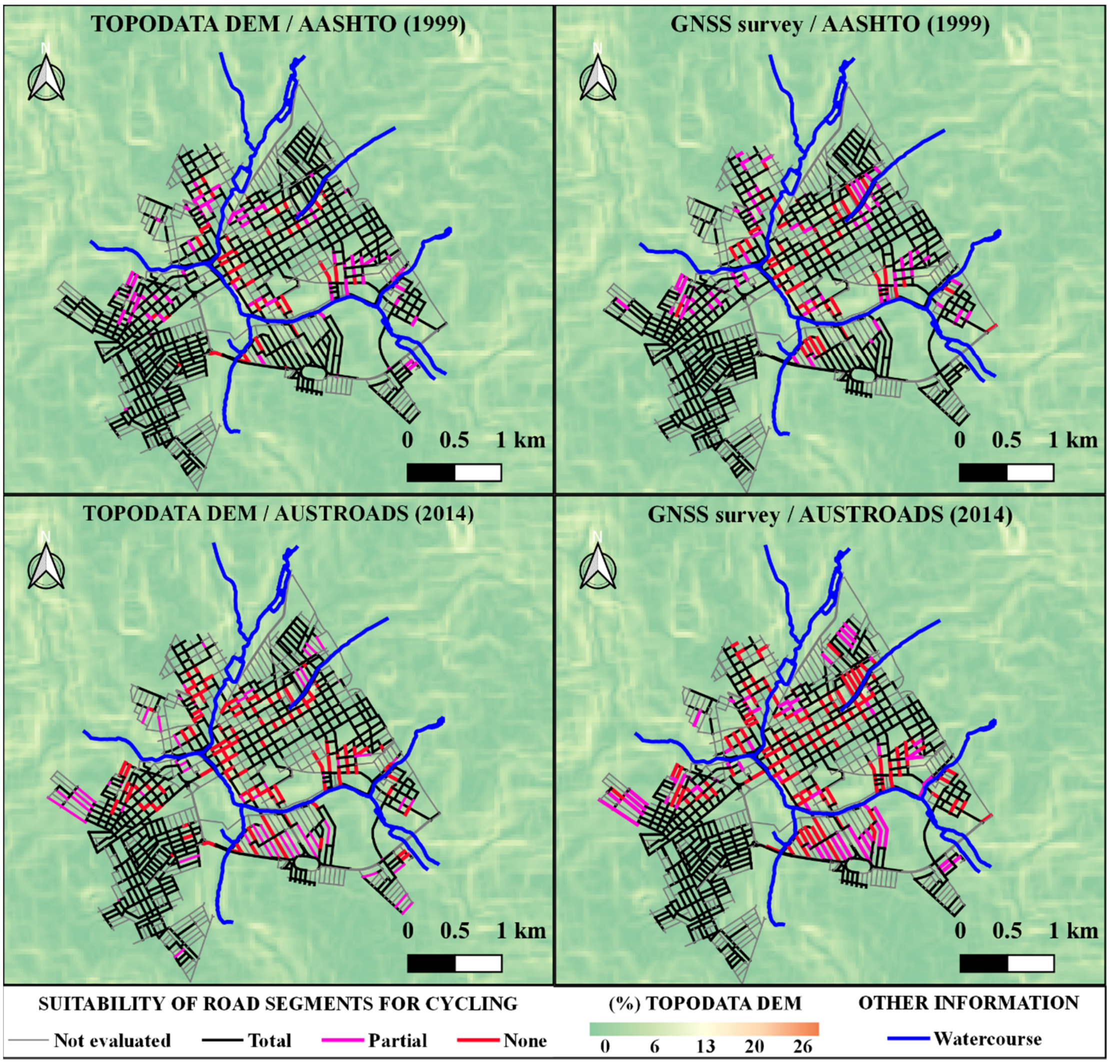

Figure 7. Suitability of road segments for cycling

4. CONCLUSIONS

This study sought to evaluate the TOPODATA DEM as a source of altimetric information to help those Brazilian municipalities that lack local topographic surveys devising urban mobility plans that emphasize active transport. By means of a case study restricted to the urban area of a small-sized Brazilian city, the quality of the spatial data extracted from the DEM was evaluated in terms of its absolute altimetric positional accuracy, as well as its usability in identifying road segments suitable for cycling according to their average slopes.

The methodology officially required by the DSG (PEC-PCD) suggested the altimetric positional quality class A of the DEM only for the 1:100,000 or smaller map scales, which are rarely used for urban planning purposes. For the map scale 1:50,000, which is often used in the early stages of urban planning, the TOPODATA DEM assumed class B and, therefore, an altimetric positional quality similar to the analogue class A products on the same map scale was suggested. However, for cycling planning stages that require greater detailing of the terrain and, consequently, must be worked on larger scales, such as small-area and corridor-level planning, the DEM did not present satisfactory altimetric positional quality; therefore, it cannot be recommended.

Regarding the differences between the homologous altitudes, the Global Moran's Index (I = 0.591) suggested a moderate to strong positive spatial autocorrelation of this variable, and a slight tendency of the error propagation was observed along the streamlines, in addition to the influences of the built environment (elevated structures) on the altimetric quality of the spatial data, which corroborates well with other studies in the literature.

As current cycling planning benefits from the GIS platforms, routing algorithms have increasingly been based on minimizing the sum of the cycling impedances of road segments, assigned accordingly to slope intervals, as in Lowry *et al*. (2016) or Monari *et al.* (2019). In this sense, this study also illustrated the importance of evaluating the TOPODATA DEM in terms of its usability, to know whether or not it can be recommended for estimating the average slopes of the road segments in urban areas.

Although, in some cases, the TOPODATA average slopes differed substantially from those measured in the field, the paired samples did not differ statistically, and regardless of the criterion adopted for the acceptable gradient lengths for cycling, more than 82% of the road segments had the same classification for the two sources of altimetric information. However, these results may not be extended to larger areas or even to other municipalities with different terrain features, which is why future work is suggested to employ the methodology of this study for understanding such cases. Furthermore, the authors suggest that the quality of spatial data from the DEM be assessed using international and more widespread standards, in order to evaluate the relevance of current guidelines in the Brazilian context.

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