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Cycling Planning in Small-Sized Brazilian Cities Based on Open Data Geoprocessing

O Planejamento Cicloviário em Cidades Brasileiras de Pequeno Porte Baseado no Geoprocessamento de Dados Abertos

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Abstract: The objective of this paper is to propose a method to systematize cycling planning in small-sized Brazilian cities based on open data, such as census data, collaborative mappings, and Digital Elevation Models, seeking to assist in the elaboration of municipal urban mobility plans, and that can be adapted to other countries with similar characteristics and that have equivalent information. The proposed method is summarized in four steps: geoprocessing of open spatial data, which allows the georeferencing of potential cycling demand and trip attractors, as well as updated representations of road systems; definition of the subsets of origins and destinations of the cycling routes to be identified using Dijkstra's algorithm, in order to minimize the overall cost associated with the road segments' operational quality for cycling; impedance assignment to road segments based on their average slopes and cycling Levels of Traffic Stress; and assessment of these road segments' proportions in the identified cycling routes (Cycling Potential Index). Examples of the proposed method's application were carried out in two Brazilian cities, Bariri-SP and Bocaina-SP, through which it was possible to define, for both cities, continuous and interconnected cycling axles, accessible to most of the study areas' potential cyclists. Therefore, despite the obvious importance of conducting specific research and field surveys in each Brazilian city for greater reliability of the results, the proposed method can contribute to the popularization of cycling in utilitarian trips and to the strengthening of the "bicycle culture" still in force in small-sized Brazilian cities.

Keywords: Bicycle. Small-sized city. Open data. Level of Traffic Stress.

Resumo: O objetivo deste trabalho é propor um método para sistematização do planejamento cicloviário em cidades brasileiras de pequeno porte baseado em dados abertos, como dados censitários, mapeamentos colaborativos e Modelos Digitais de Elevação, buscando contribuir com a elaboração de planos municipais de mobilidade urbana, e que possa ser adaptado a outros países com características semelhantes e que possuam informações equivalentes. O método proposto é resumido em quatro etapas: geoprocessamento de dados espaciais abertos, permitindo o georreferenciamento da demanda cicloviária potencial e dos polos atratores de viagem por bicicleta, assim como a representação atualizada de sistemas viários; definição dos subconjuntos de origens e destinos das rotas cicláveis a serem identificadas pelo algoritmo de Dijkstra, de forma a minimizar o custo generalizado associado à qualidade operacional de segmentos viários ao ciclismo; atribuição de impedâncias aos segmentos viários baseada em suas declividades médias e níveis de estresse ao ciclismo; e avaliação da proporção destes segmentos viários nas rotas cicláveis identificadas (Índice de Potencial Ciclável). Exemplos de aplicação do método foram conduzidos a duas cidades brasileiras, Bariri-SP e Bocaina-SP, a partir dos quais foi possível definir, para ambas, eixos cicláveis contínuos, interconectados e acessíveis à maioria dos ciclistas das áreas de estudo. Portanto, apesar da notória importância de serem conduzidos estudos específicos e levantamentos de campo em cada cidade brasileira para uma maior confiabilidade dos resultados, o método proposto pode contribuir com a popularização da bicicleta em viagens utilitárias e com o fortalecimento da "cultura da bicicleta" ainda em vigor nestas menores cidades brasileiras.

Palavras-chave: Bicicleta. Cidade de pequeno porte. Dados abertos. Nível de estresse ao ciclismo.

1 CYCLING PLANNING IN SMALL-SIZED BRAZILIAN CITIES

The urban mobility system of Brazilian cities is characterized by the prioritization of individual motorized transport, although active transport is responsible for a large part of the daily trips in most of them: according to recent reports from the Brazilian Urban Mobility Information System, walking and cycling account for more than 42% of the transport modal matrix in the cities analyzed (ANTP, 2020). Furthermore, although the elaboration of urban mobility plans that propose practical solutions for the emancipation of these transportation modes is a legal requirement for Brazilian municipalities with a population of over 20,000 inhabitants or of tourist interest (popularly known as the "Mobility Law"), it is estimated that only 14% of them have actually completed plans (BRAZIL, 2012; SEMOB, 2021).

The antagonism between the legal requirement and the necessary instrumentalization for the elaboration of urban mobility plans is critical in small-sized Brazilian cities, that is, whose population is limited to 100,000 inhabitants (IBGE, 2016), which rarely have basic information such as origin-destination data, traffic studies, local topographical surveys, etc., as well as specialized technical staff: more than 25% of Brazilian municipalities claim that they do not have any transportation policy management department and, among those that do, there is a predominance of departments exclusive to transportation policies in larger urban centers; moreover, regarding the educational level of the heads of these departments, it is estimated that only 35.9% of these authorities have completed higher education or postgraduate studies, this percentage being even lower when referring exclusively to the small-sized Brazilian cities (IBGE, 2018).

Although in some countries a homogeneous distribution of bicycle use can be observed in different age groups and social classes, a consequence of public policies to encourage active transport and restrict motorized traffic, according to Sousa (2012), this logic cannot be extended to emerging countries, such as Brazil, where the cycling demand is mostly composed of men of working age with lower purchasing power to afford individual motorized transport. However, recent studies have suggested different considerations about the cycling demand of small-sized Brazilian cities. In 2018, the results of the National Survey on the Profile of Brazilian Cyclists were presented, a study carried out in partnership between members of the Brazilian Active Transport Association and researchers from the Federal University of Rio de Janeiro (or UFRJ, which in Portuguese stands for *Universidade Federal do Rio de Janeiro*), whose objective was to profile the Brazilian cyclist based on an extensive data collection from 7,644 participants in 25 different Brazilian cities, selected based on their high rate of bicycle use. Soares and Guth (2018), benefiting from the collected data, compiled information regarding the 11 small-sized cities included in the survey, which are distributed throughout the five Brazilian regions and whose number of inhabitants varies from 8,271 to 91,271, in order to highlight the main sociodemographic characteristics of the cycling demand in these smaller urban centers, generalizable to other small Brazilian municipalities.

One of the main differences between the largest and smallest Brazilian urban centers, regarding the bicycle use, is the number of women who ride. On average, 35% of the total number of cyclists in small-sized cities are women, in contrast to the 7% average observed in large cities (CICLOCIDADE, 2015; SOARES; GUTH, 2018). This can be explained by the fact that the smallest Brazilian municipalities have lower violence rates, both in general terms and in traffic, when compared to metropolitan regions, encouraging the bicycle use even at night by individuals who are systematically more susceptible to robberies and other transgressions, such as women (NERI, 2012). Furthermore, it is estimated that, on average, 90% of cyclists in small-sized Brazilian cities have completed elementary school, and about 64% declare having a monthly income of up to 2 minimum wages. With regard to customs and frequency of bicycle use, more than 68% of these cyclists claim to use the bicycle daily; 83% do not benefit from integration with other transportation modes (partly explained by the short daily trips); and more than 64% of respondents declare that they do not need more than twenty minutes to reach their destinations (SOARES; GUTH, 2018).

In addition to the characteristics intrinsic to cyclists previously mentioned, the bicycle use is also influenced by the geometric and operational conditions of the route on which they travel (FHWA, 2006). Distance or travel time, for example, are closely related to urban design and the road segments' operational quality, as cyclists seek to deviate from segments under precarious conditions in order to maintain a homogeneous level of safety and comfort throughout their utilitarian trips (AULTMAN-HALL; HALL; BAETZ, 1997; STINSON; BATH, 2003; BROACH; DILL; GLIEBE, 2012). By means of a systematic review of research developed in the Brazilian context, Silveira and Maia (2015) argue that traffic insecurity is the factor that most discourages cycling in Brazilian cities of different sizes, which may be related to several reasons such as excessive intersections along the route and poor treatment of these intersections.

The existence of bike lanes or bike paths is also repeatedly mentioned in the literature as one of the main factors underlying the cyclists' route choice, whether in the case of countries that commonly have them or not (HUNT; ABRAHAM, 2007; LARSEN; EL-GENEIDY, 2011; KANG; FRICKER, 2013; PITILIN, 2016), and the main criteria for the inclusion of these facilities refer to two other important factors that influence the bicycle use in the urban context, that is, the volume and speed of motor vehicle traffic (LTSA, 2004; TRANSPORT SCOTLAND, 2010). Other factors such as availability of space (TOOLE, 2010), roads' slope and pavement condition (MENGHINI et al., 2010; WINTERS et al., 2011) and land use (MELLO; PORTUGAL, 2017) can also influence cycling.

In small-sized Brazilian cities, however, the ease of applying actions to mitigate motorized traffic (traffic calming), the still expanding road systems, limited municipal budgets and lower road complexity when compared to larger cities (fewer arterial and rapid transit roads), the smaller motorized traffic volumes and speeds, the predominance of unsignalized intersections, etc., justify the emphatic cycling planning of mixed traffic, when cyclists share the road segments with motorized vehicles with no need for cycling facilities. According to Silva (2018), the frequency and severity of accidents involving cyclists are directly related to the level of interaction between them and motorized traffic. In this context, recent data from INFOSIGA-SP (2020), for example, suggest that less than 35% of traffic accidents with death involving cyclists between the period 2015 to 2020, in the State of São Paulo, occurred in small cities, which represent more than 87% of São Paulo cities (MONARI; SEGANTINE, 2020).

Currently, almost all stages of territorial transportation planning benefit from Geographic Information Systems (GIS), which allows the georeferencing of different transportation modes' potential demand, the allocation of facilities, the definition of routes, etc. by means of spatial data geoprocessing. In this context, considering that several Brazilian digital repositories have useful information for cycling planning that are often unknown by national transportation planners, such as census data, collaborative mapping, and Digital Elevation Models (DEM), the objective of this paper is to propose a method to systematize cycling planning in small-sized Brazilian cities based on open data, seeking to assist in the elaboration of municipal urban mobility plans, and that can be adapted to other countries with similar characteristics and that have equivalent information. Examples of the method's application were carried out in Bariri and Bocaina, two Brazilian cities located in the State of São Paulo with estimated population of, respectively, 35,844 and 12,571 inhabitants (IBGE, 2021). The selection of such cities is justified by the fact that Bariri has its urban mobility plan completed (BARIRI CITY HALL, 2012), allowing one to compare the results of the proposed method's application with the local cycling planning already in practice; and Bocaina has recently been recognized by the state government as a city of tourist interest (BOCAINA CITY HALL, 2019).

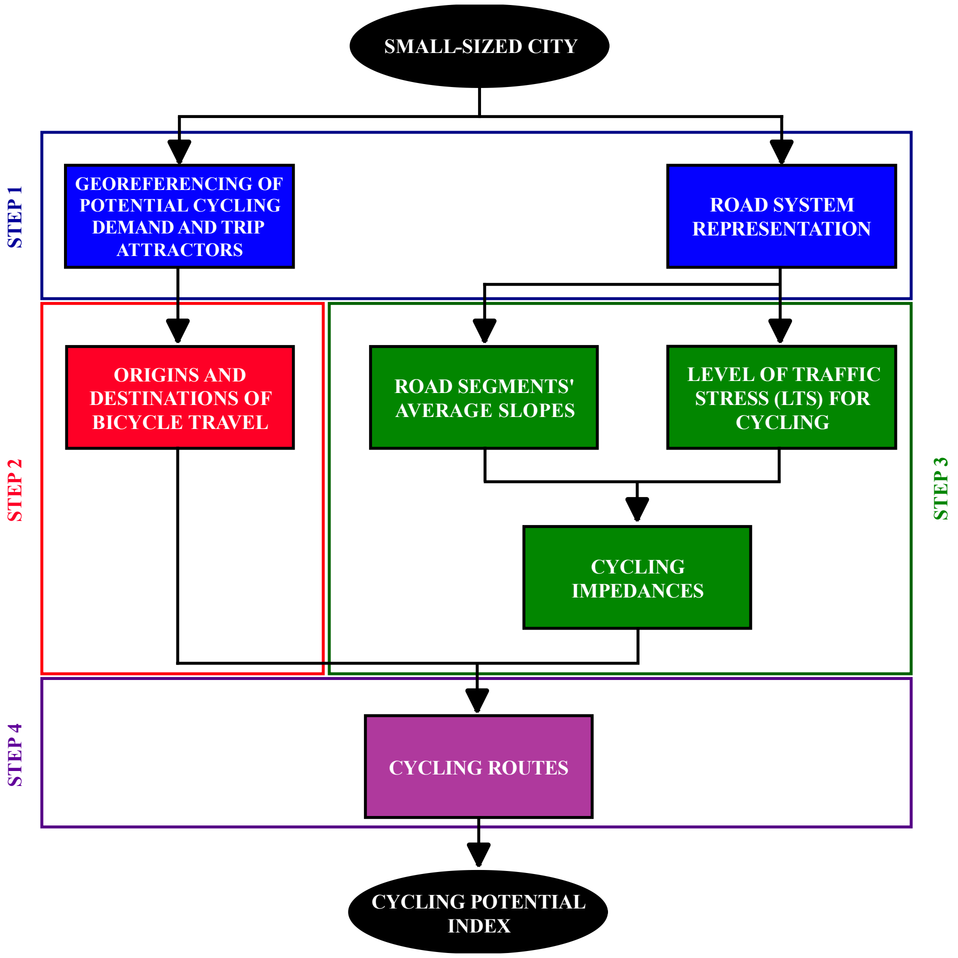
2 METHOD

This section details the materials and the proposed method for systematizing cycling planning in small-sized Brazilian cities, whose step sequence is shown in Figure 1.

2.1 Step 1: Open data geoprocessing

The first step of the proposed method consists of geoprocessing the open data that allow georeferencing the potential cycling demand and trip attractors, as well as representing the road system of a particular place of study in an up-to-date way. In this context, although the geoprocessing of spatial data should benefit from GIS platforms, specific GIS for solving transportation problems are rarely available to researchers and other professionals due to their high cost. Therefore, QuantumGIS (QGIS), an open-source GIS freely available for download, can serve as an interesting alternative to these specific software, since with each QGIS update new complements are made available to users. QGIS version 3.8.2 "Zanzibar" was used in this work.

Figure 1 – Method for systematizing cycling planning in small-sized Brazilian cities.



Source: Authors (2022).

2.1.1 ROAD SYSTEM REPRESENTATION

Transportation planning requires the representation of existing road systems through georeferenced vector features. In 2016, the Brazilian Institute of Geography and Statistics (or IBGE, which in Portuguese stands for *Instituto Brasileiro de Geografia e Estatística*) made available in its digital repository vector layers representing the extensions comprised between blocks for all 5,570 Brazilian municipalities, based on the 2010 Brazilian National Demographic Census, and which have been periodically updated since then. Up to the time this work has been carried out, the most recent data refer to the existing features in the year 2020.

Although this information presents itself as an interesting starting point for the representation of a given updated road system, transportation planners generally use other sources of information based on collaborative mapping, such as OpenStreetMap (OSM), which, in addition to sketching the road system, also characterizes most features by attributes such as functional hierarchy, speed limit and traffic flow direction. QGIS, for example, by means of a complement intitled "OSMDownloader", allows users to filter the OSM data within the study area.

From the available vector layers, it is possible to build a graph, that is, the simplification of the original features by subdividing them into road segments (edges), followed by the creation of a point layer representing their intersections (nodes). Based on the start and end nodes of each road segment, it is possible to assign to all of them, in a specific column of the attributes table, values representing their traffic flow directions (1 for forward direction, that is, from the start to the end node of the segment; -1 for reverse direction, that is, from the end to the start node of the segment; and 0 for both directions), defined from information already existing in the original OSM features, *in situ* visits, and ground level navigation using the Google Streetview, so that the routes to be identified in later stages comply with these restrictions. By means of the methodology presented above, each road segment can also be assigned its speed limit, number of traffic lanes and existence of centerlines (*dummy* variable), input variables of the traffic stress model presented in the next sections.

2.1.2 GEOREFERENCING OF POTENTIAL CYCLING DEMAND AND TRIP ATTRACTORS

Still referring to the 2010 Brazilian National Demographic Census, georeferenced vector layers referring to the census sectors (polygons) are also available in the IBGE official repository, which are properly coded according to the city in which they are located, allowing them to be associated with information also made available by the Institute in the form of Microsoft Excel spreadsheets, such as the resident population and their respective sociodemographic characteristics (age, income, etc.).

In this context, based on the results of the National Survey on the Profile of Brazilian Cyclists and on the subsequent study developed by Soares and Guth (2018), both already mentioned in the introductory section, which suggest sociodemographic characteristics of cycling demand in small-sized Brazilian cities included in the research likely to be generalizable to other small Brazilian municipalities, it is possible to proceed with the georeferencing of the potential cycling demand. Two of these characteristics were selected for this research: age and income, which were aggregated as shown in Table 1. Thus, knowing the population in each census sector belonging to these groups, it is possible to proceed with their weighting by their respective tabulated percentages, resulting in the number of people, in each sector, with potential interest in the bicycle use.

Table 1 – Percentage of potential cyclists for different age-income combinations.

Income/Age	10 to 29	30 to 49	50 to 69	70+	Total
Up to 2 minimum wages	27.5	20.5	13.6	2.2	63.8
2 to 5 minimum wages	6.7	5.0	3.3	0.5	15.5
5+ minimum wages or no response	8.9	6.7	4.4	0.7	20.7
Total	43.1	32.2	21.3	3.4	100

Source: Authors (2022).

It is worth noting that, concerning the Brazilian population income, the data provided by the IBGE refer only to individuals aged 10 years or more, therefore, two of the cities included in the original publication (Gurupi-TO and Mambaí-GO) were excluded from this analysis, as they include significant percentages of individuals under 10 years of age in the data collection. Furthermore, the Brazilian demographic census is periodically carried out every 10 years, and the one scheduled for 2020 could not be managed due to the guidelines to contain the Coronavirus pandemic (COVID-19). Thus, although the census data included in the research refer to a context of more than a decade ago and may not reflect the current reality of the study area, due to the methodological approach of this research, the authors chose to work with such official data.

Bicycle use is encouraged as a greater number of facilities characterized as trip attractors, such as industries, schools, supermarkets, clubs, churches, etc. become accessible. In addition, urban areas contemplated with varied land use, for example, predominantly residential areas, but occupied by multiple commercial facilities, also benefit from a large number of bicycle trips (MELLO; PORTUGAL, 2017; CERVERO; DENMAN; JIN, 2019). In this context, the georeferencing of trip attractors can benefit, for example, from a thorough search for these facilities on platforms such as Google Maps.

2.2 Step 2: Subsets of origins and destinations in the network

Once the potential cycling demand, aggregated by census sectors, is georeferenced, it is possible to proceed with the definition of the origins of the cycling routes along the network. For this, it is first necessary to filter the urban census sectors belonging to the study area, and then the information contained in each sector must be transferred to the statistical grid also provided by IBGE, which consists of a system of regular cells (0.04 km^2) substantially smaller than the original polygons. For cases where the same cell is intercepted by more than one census sector, the transferred information must be weighted by the intersecting areas of each one of these sectors. Finally, the network nodes closest to the centroids of each grid cell must be identified, from which the cycling routes must be calculated, weighted by the accumulated demand at each node, as described in the next sections.

Analogously, based on the georeferencing of trip attractors, it is also possible to identify in the statistical grid which of its cells concentrate the largest number of these facilities, which should be characterized as a subset of cycling routes destinations in the network. It is important to highlight that, as well as the origins, the destinations of bicycle trips, eventually, can also be weighted in terms of their potential to attract cyclists (MCNEIL, 2011). However, due to the lack of studies specific to small-sized Brazilian cities that seek to quantify this potential, in this work, multipliers for destinations were not considered.

2.3 Step 3: Cycling impedances assignment

The identification of optimal routes is a process addressed in the literature by several authors as the "shortest path problem", which repeatedly benefit from Dijkstra's (1959) algorithm based on graph theory. Basically, when road segments are represented in a simplified way by edges, to which weights are assigned depending on their length or travel time, and their intersections are represented by nodes, the shortest path between a given origin-destination pair is the sequence of continuous edges whose accumulated distance or travel time is minimal, respecting the traffic flow directions allowed in the network. The constant evolution of GIS platforms, however, has enabled alternative approaches that assess road segments and intersections according to their impedance, that is, the overall cost associated with their operational quality for cycling (KLOBUCAR; FRICKER, 2007; LOWRY et al., 2012; MONARI et al., 2018).

In this context, it is proposed in this work that cycling impedances be assigned to road segments as presented by Eq. (1), whose input variables are detailed in the following subsections.

$$I_e = f_{slope,e} \times \left(L_e \times f_{LTS,e} + L_{penalty,e}\right) \quad (1)$$

where I_e is the cycling impedance for road segment *e*; L_e is the actual length of the road segment *e*; $f_{LTS,e}$ and $f_{slope,e}$ are, in this order, the equivalence and slope factors related to the road segment *e*; and $L_{penalty,e}$ is a penalty (length-equivalent) of the road segment *e* for intersections.

2.3.1 LEVEL OF TRAFFIC STRESS (LTS) FOR CYCLING

Equations, indexes and scoring systems developed to assess the operational quality of roads segments and intersections to cycling are usually described in the literature as bicycle level of service models. Although several of these models have been proposed internationally in recent decades (EPPERSON, 1994; DIXON, 1996; LANDIS; VATTIKUTI; BRANNICK, 1997; HARKEY et al., 1998; JENSEN, 2007; BEURA et al., 2018), little effort have been carried out in the Brazilian context with similar objectives (PROVIDELO, 2011; CARDOSO; CAMPOS, 2016). In addition, when applied directly to case studies conducted in Brazilian cities (KIRNER, 2006; MAGALHÃES; CAMPOS; BANDEIRA, 2015), even the medium-sized ones, the models developed internationally reflect difficulties, especially concerning the collection of predictive variables; and limitations, mostly related to the subjectivity of the input variables' assessment, and the great importance of cycling infrastructure such as bike lanes and bike paths in the final assessment of the road, which are rarely present in Brazilian cities (MONARI; SEGANTINE, 2020).

In this context, given the lower road complexity of small-sized Brazilian cities, cycling planning can benefit from simpler, more objective approaches, such as the Level of Traffic Stress (LTS) model, which suggests different assessments for bike lanes and mixed traffic situations (MEKURIA; FURTH; NIXON, 2012). For both cases, the LTS classification is subdivided into 4 levels, LTS4 being the worst and LTS1 the best, which in turn can be associated with the classification of the adult population proposed by Geller (2006): "Strong and fearless", potentially willing to ride a bike under any traffic conditions; "Enthused and confident", who tolerate intermediate levels of traffic stress; "Interested but concerned", which are only willing to travel through low-stress road segments; and "No way no how", that is, adults that show no interest in riding a bike.

Regarding mixed traffic situations, the predictive variables of the LTS model updated from 2016 are the number of traffic lanes per direction, the speed limit, the existence of marked centerlines, and the Average Daily Traffic (ADT), as shown in Table 2 (FURTH; MEKURIA; NIXON, 2016). For places where speed measurements are available, however, it is suggested the use of the measured speeds' average value in cases where it exceeds the legal limit assigned according to the functional hierarchy of the road, which, for the smallest Brazilian municipalities, is not always clearly defined (MONARI; SEGANTINE, 2019). The LTS criteria for classifying bike lanes are shown in Table 3.

Table 2 – LTS in mixed traffic.

Speed limit (km/h)	**No marked centerline and ADT [a] ≤ 3,000 vehicles per day**	**Through lanes per direction**		
		1	**2**	**≥ 3**
Up to 40	LTS1	LTS2	LTS3	LTS4
50	LTS2	LTS3	LTS4	LTS4
60 or higher	LTS4	LTS4	LTS4	LTS4

[a] ADT: Average Daily Traffic.

Source: Furth, Mekuria, and Nixon (2016).

Table 3 – LTS criteria for bike lanes classification.

Number of lanes per direction	**Bike lane width [a] (m)**	**Prevailing speed (km/h)**					
		≤ 40	**50**	**60**	**65**	**70**	**≥ 80**
1	≥ 1.80	LTS 1	LTS 2	LTS 2	LTS 3	LTS 3	LTS 3
1	1.20 - 1.60	LTS 2	LTS 2	LTS 2	LTS 3	LTS 3	LTS 4
2	≥ 1.80	LTS 2	LTS 2	LTS 2	LTS 3	LTS 3	LTS 3
2	1.20 - 1.60	LTS 2	LTS 2	LTS 2	LTS 3	LTS 3	LTS 4
3	Any width	LTS 3	LTS 3	LTS 3	LTS 4	LTS 4	LTS 4

[a] Includes any marked buffer next to the bike lane.

Source: Furth (2017).

Despite the ease of application and the reduced set of input variables of the presented LTS criteria, much is discussed about the need to validate the model through measures of cyclists' physiological stress (WANG et al., 2016; CHEN et al., 2017; FREITAS et al., 2018; FERENCHAK; MARSHALL, 2020; HUERTAS et al., 2020; COBB; JASHAMI; HURWITZ, 2021), and the possible inclusion of other factors also identified as stressors to cycling, such as narrow lanes, steep slopes, damaged pavement, heavy traffic, and the presence of parked vehicles or other obstacles on the road (SORTON; WALSH, 1994; VIEIRA et al., 2016; ZEILE et al., 2016; CAVIEDES; FIGLIOZZI, 2018; KYRIAKOU et al., 2019; FITCH et al., 2020; RYBARCZYK et al., 2020). Thus, the reproduction of the proposed method, by other researchers and municipal authorities may benefit from changes to the LTS criteria, such as those proposed by Rodrigues, Silva, and Teixeira (2022), or even by other adaptations, provided that large-scale information is available on the factors included (land subdivision projects, completed or in progress, for consultation of road widths; urban pavement management system; cadastral surveys of aesthetic and road safety promotion elements, such as trees and lampposts; land use maps, etc.). For the case study, in addition to the predictive variables of the LTS model itself, only road segments' average slopes were considered when assigning impedances, as explained in the next subsection.

The equivalence between road segments with different geometric and operational characteristics, or between different cycling facilities, can benefit from Marginal Rates of Substitution (MRS), a concept adapted from economic theory that seeks to define the rate at which consumers choose to replace one product for another (SALVATORE, 1984). For example, Hood, Sall, and Charlton (2011) suggest that cyclists choose to travel up to 1 kilometer along bike lanes or bike paths, replacing, in this order, 490 and 570 meters on roads that do not have them. Broach, Dill, and Gliebe (2012) argue that a 1% relative increase in travel distance results in a 9% decrease in the probability of cyclists choosing a particular route in their utilitarian trips; that traveling on bike paths is equivalent to a relative decrease of 16% in travel distance in relation to roads that do not have them; and that cyclists are willing to increase their travel distances by up to 37% to avoid road segments with upslopes between 2 and 4%; 120% for upslopes between 4 and 6%; and 323% for upslopes greater than 6%.

In this context, the equivalence factors assigned to each LTS classification should be based on the maximum percentage deviation acceptable by cyclists, in relation to their most direct routes, in order to avoid road segments with low operational quality, being suggested by some case studies conducted in Brazil values between 15 and 25% (SEGADILHA, 2014; TUCKER; MANAUGH, 2016). In other words, adopting the strictest limit (15%), it is understood that a cyclist is willing to travel up to 115, 110 and 105 meters on a road segment classified as LTS1 instead of 100 meters of the same road segment if classified as, respectively, LTS4, LTS3 and LTS2. Thus, the equivalence factors (f_{LTS}) adopted for each increasing LTS classification are 1.00, 1.05, 1.10 and 1.15.

In addition to bike lanes and shared spaces between cyclists and motor vehicles, the LTS model also proposes classifications for unsignalized crossings, that is, when minor streets meet a major street without the existence of traffic lights, depending on the speed limit and the number of lanes of the latter, a new LTS classification can be assigned to road segments with the lowest functional hierarchy close to the intersection, simulating a transfer of the traffic stress of the street being crossed (MEKURIA; FURTH; NIXON, 2012). Adaptations of this methodology, however, have been proposed in recent studies, considering that only part of the "difficulty" in traveling through the segment with lower operational quality is transferred to the others, that is, a part of these better segments, close to the intersection, resembles the segment with worse operational quality, which is understood as a penalty, and for that, influence buffers of up to 25 meters consonant to the LTS scale must be considered (CERVERO; DENMAN; JIN, 2019; PRITCHARD; FROYEN; SNYZEK, 2019). In this work, buffers of, respectively, 0, 5, 10 and 15 meters were considered for each increasing LTS classification, and the mathematical formulation for calculating the length-equivalent penalty ($L_{penalty}$) of a given road segment e is presented by Eq. (2).

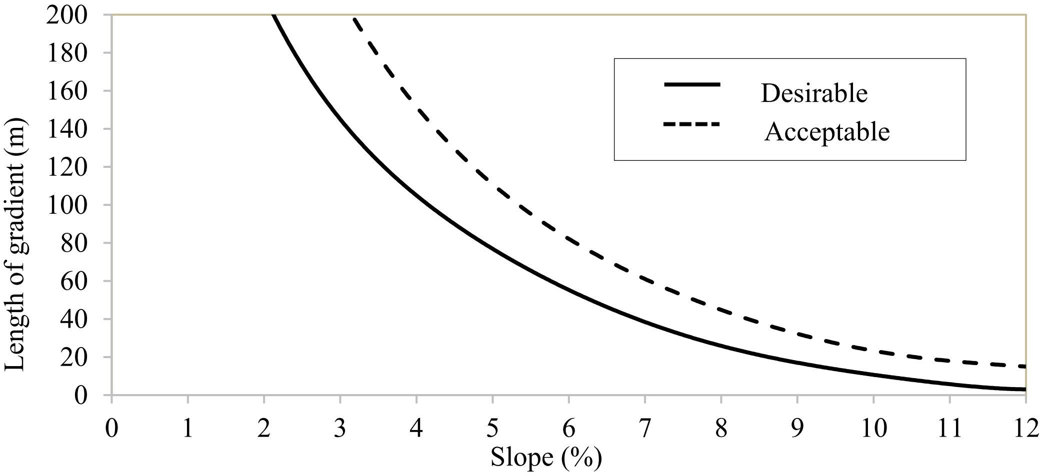
$$L_{penalty,e} = \sum_{b=1}^{m} w_{eb} \times (B_b - B_e) \times (f_{LTS,b} - 1{,}00) \times \gamma_{eb} \quad (2)$$

where w_{eb} is equal to 1 when road segment e is connected to road segment b, and 0 otherwise; B_e and B_b are, in this order, the influence buffers for road segments e and b; $f_{LTS,b}$ is the equivalence factor of the road segment b regarding its LTS classification; γ_{eb} is equal to 1 when $LTS_b > LTS_e$, and 0 otherwise; and m is the number of road segments in the network.

2.3.2 ROAD SEGMENTS' AVERAGE SLOPES

Many cycling planning handbooks, such as the Cycling Aspects of Austroads Guides (AUSTROADS, 2014), have sought to propose, regarding uphill slopes, the maximum lengths of gradient up to which road segments are acceptable to cycling (Figure 2), through which it is possible to assign to each road segment its respective slope factor according to Eq. (3).

Figure 2 – Desirable and acceptable cycling lengths of gradient.



Source: Austroads (2014).

$$f_{slope,e} = \begin{cases} 1.00, & \text{if slope} < 3\% \text{ or } L_e \leq L_{ac,e} \\ \dfrac{L_e}{L_{ac,e}}, & \text{otherwise} \end{cases} \tag{3}$$

where $f_{slope,e}$ is the slope factor for road segment *e*; and L_e and $L_{ac,e}$ are, respectively, the actual and the cycling acceptable lengths of the road segment e.

Altimetric data from the entire Brazilian territory can be extracted from a 30-meter spatial resolution DEM entitled TOPODATA, which is a derivation of the Shuttle Radar Topography Mission (SRTM) model and is provided by the Brazilian National Institute for Space Research (or INPE, which in Portuguese stands for *Instituto Nacional de Pesquisas Espaciais*). Although specific studies regarding its logical consistency, completeness, accuracy (positional and temporal) and usability are needed (IBGE, 2017), the model presents itself as an interesting tool capable of meeting the lack of aerophotogrammetric, laser scanning and levelling surveys in Brazilian cities, allowing one to assess the road segments' average slopes by extracting their start and end nodes' altitudes. Moreover, the joint analysis of these altimetric coordinates and the traffic flow directions allowed in the network makes it possible to distinguish uphill from downhill slopes.

It is important to highlight that even though steep downhill slopes make cycling unsafe, this situation was not assessed in this work, since it hardly ever discourages cycling. Therefore, descending one-way road segments were assigned slope factors equal to 1.00, and two-way road segments were duplicated so that ascending and descending movements in the network could be separately assessed.

2.4 Step 4: Road segments' shortest paths proportions

The last step of the proposed method consists of estimating the road segments' Cycling Potential Indexes (C) based on their shortest path proportions, an adaptation of the concept of "betweenness centrality", which is frequently used in the literature aimed at assessing the relative importance of road segments in the network (BRANDES, 2008; MCDANIEL; LOWRY; DIXON, 2014). In this context, it is worth mentioning that even though some studies that benefited from similar methodologies suggest that cycling routes should be kept to a reachable distance threshold for bicycles, often between 3 and 8 km (GEIPOT, 2011; MCNEIL, 2011; MCDANIEL; LOWRY; DIXON, 2014; LOWRY; FURTH; HADDEN-LOH, 2016), this boundary condition, with few exceptions, can be disregarded for small-sized Brazilian cities, which mostly have compact configurations. Furthermore, it is necessary to consider that, in order to respect the network traffic flow directions, many cyclists choose different round-trip routes on their utilitarian trips. Thus, both going and leaving optimal routes for each origin-destination pair in the network must be translated in terms of centrality.

In short, the set of nodes of a graph G is represented as $N(G) = \{n_1, \ldots, n_n\}$. If the subsets $I \subset N(G)$ and $J \subset N(G)$ are defined, which refer respectively to the cycling routes' origin (*i*) and destination (*j*) nodes in the network, the latter being of cardinality k (number of nodes of J), the shortest paths proportion for a given road segment *e* can be estimated using Eq. (4 to 6) below:

$$C_e = \frac{\left[\sum_{i\in I, j\in J} \sigma_{ij}^*(e) \times D_i + \sum_{i\in I, j\in J} \sigma_{ji}^*(e) \times D_i\right]}{2 \times k \times \sum_{i\in I} D_i} \tag{4}$$

$$\sigma_{ij}^*(e) = \begin{cases} 1, & \text{if the road segment } e \text{ belongs to } \sigma_{ij}^* \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

$$\sigma_{ji}^*(e) = \begin{cases} 1, & \text{if the road segment } e \text{ belongs to } \sigma_{ji}^* \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

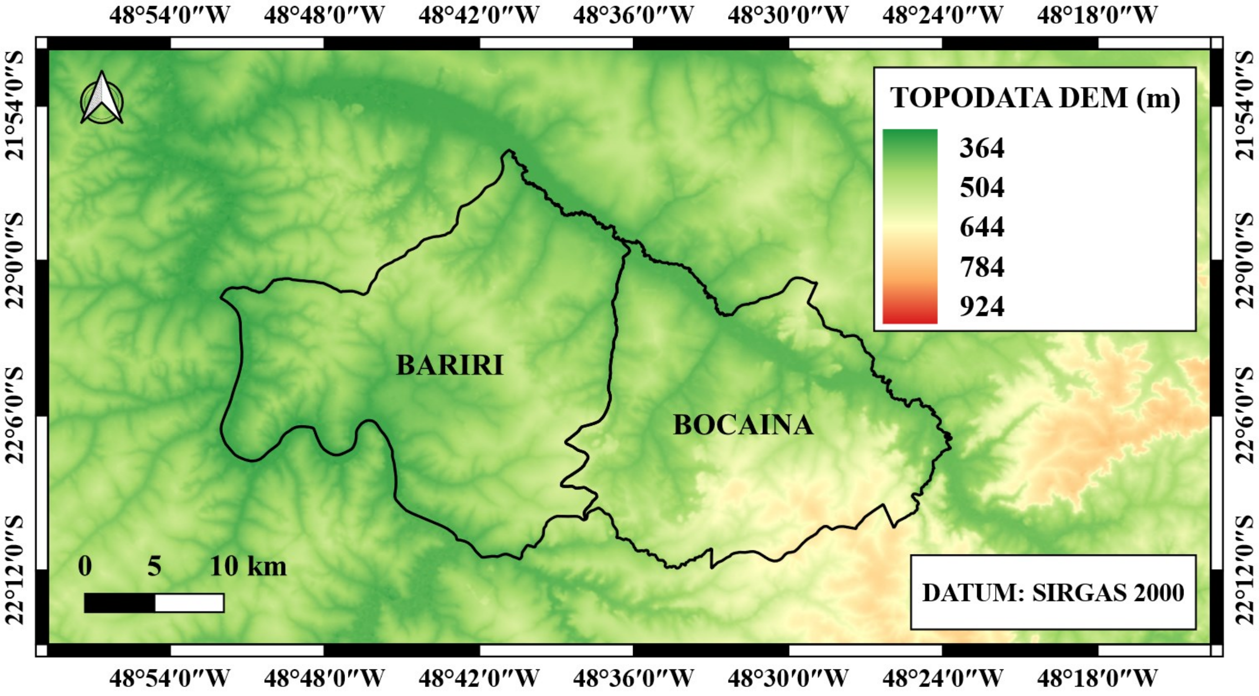
where C_e is the Cycling Potential Index of the road segment *e*; σ_{ij}^* and σ_{ji}^* are, in this order, the paths that minimizes the sum of impedances between nodes i and j, and between nodes j and *i*; and D_i is the potential cycling demand accumulated at node *i*.

After identifying the road segments with the greatest cycling potential, continuous infrastructures can be defined, and their coverage must be evaluated by means of the percentage of potential cycling demand served by areas of influence delimited by 400-meter buffers from them (VALE; SARAIVA; PEREIRA, 2016).

3 EXAMPLES OF APPLICATION OF THE PROPOSED METHOD

This section presents examples of application of the proposed method. Figure 3 shows the location map and the TOPODATA DEM for the case study. In the city of Bariri, more than 62% of the study area has slopes of less than 3% (flat terrain), while in the city of Bocaina, just under 29% of the study area is within this slope class, with the majority (65%) characterized by slopes between 3 and 8% (smoothly undulating terrain).

Figure 3 – Location map and TOPODATA DEM for the studied cities.



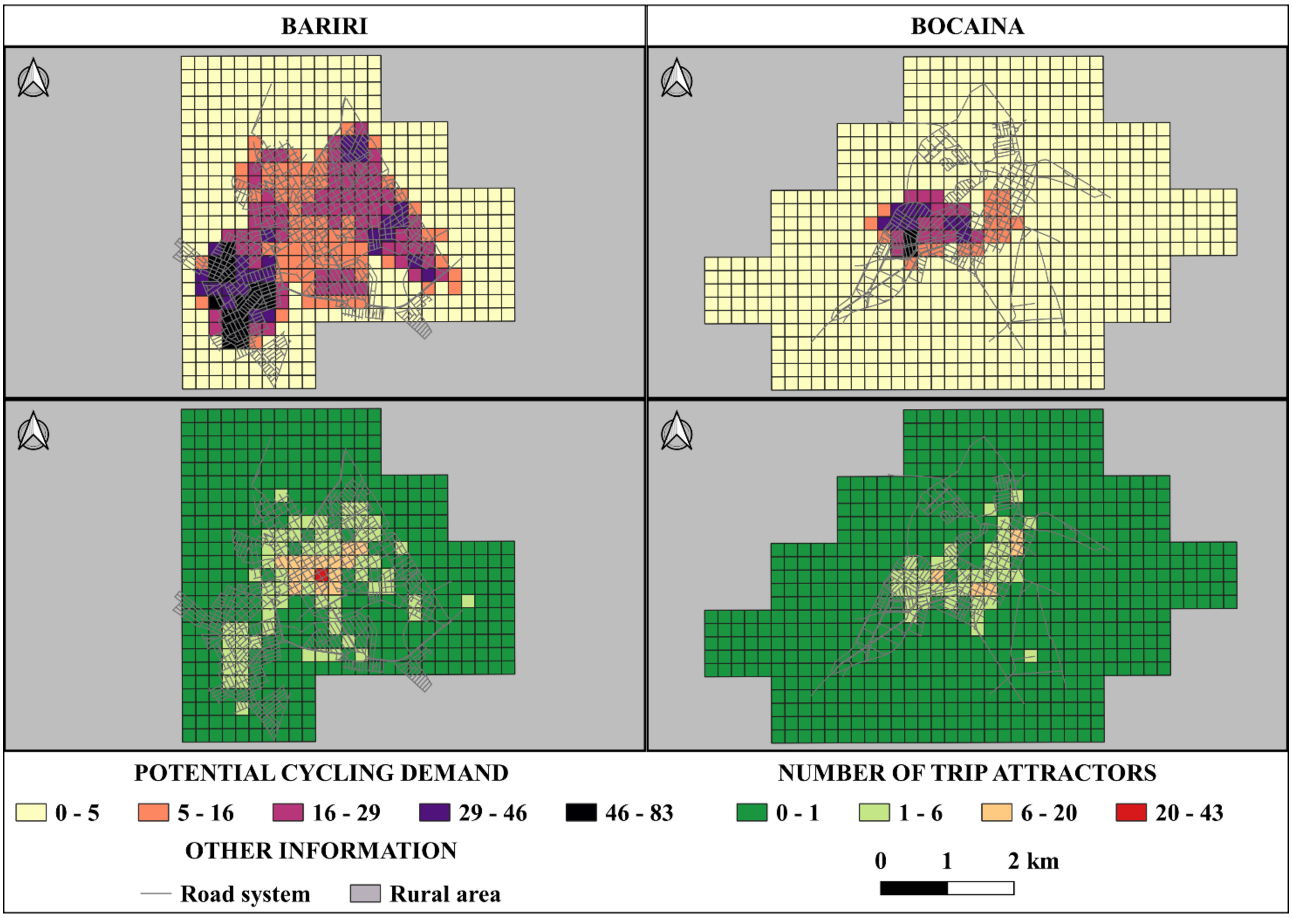
Source: Authors (2022).

Figure 4 summarizes the results of the proposed method's preliminary steps. The city of Bariri is made up of 1,853 road segments (edges) that intersect or end in 1,180 different locations (nodes); for Bocaina, these values are, respectively, 849 and 559. The georeferencing of potential cycling demand allowed the definition of subsets consisting of 278 origins of cycling routes for the city of Bariri, and 170 for the city of Bocaina. Regarding the trip attractors, 735 potential destinations for bicycle travel were georeferenced in the city of Bariri, and 168 in the city of Bocaina, from which it was possible to identify subsets of cells with higher density of these destinations, being, in that order, 77 and 41 for the cities of Bariri and Bocaina.

The LTS assessment in the city of Bariri was supported by existing speed measurements taken on major streets, and traffic counts performed in 33 locations identified from historical series available on the Google Maps platform as the ones with the highest traffic flow. Each count was performed during a 15-minute period during peak hours. The observed volumes were converted into hourly flows, considering an hourly peak factor of 0.79 (as suggested by previous studies of local traffic), and then converted into daily flows, considering that the hourly flows represent a percentage of 10% of the daily flows (DNIT, 2010). For minor streets, ADT of less than 3,000 vehicles per day were admitted. The results suggest the predominance of good LTS classifications (LTS1), except for road segments with marked centerlines and higher traffic speeds, or for the rare occasions when combinations between no marked centerlines and ADT in excess of 3,000 vehicles per day were observed in the city center. Regarding the existing cycling infrastructure, the 2.4 kilometers of unidirectional bike lanes in Bariri are rated LTS2.

For LTS assessment in Bocaina, however, there was no traffic study available, and preliminary counts carried out in some locations where the highest vehicular flows were expected showed that, even on these main streets, daily flows greater than 3,000 vehicles per day are not observed. The results suggest low levels of traffic stress across the network (LTS1), but some of the evaluated streets that promote the articulation between neighborhoods and access to trip attractors are vicinal highways or unpaved roads, whose posted speed limits are, respectively, 80 and 60 km/h, and therefore are classified as LTS4.

Figure 4 – Road system representation, and georeferencing of potential cycling demand and trip attractors.



Source: Authors (2022).

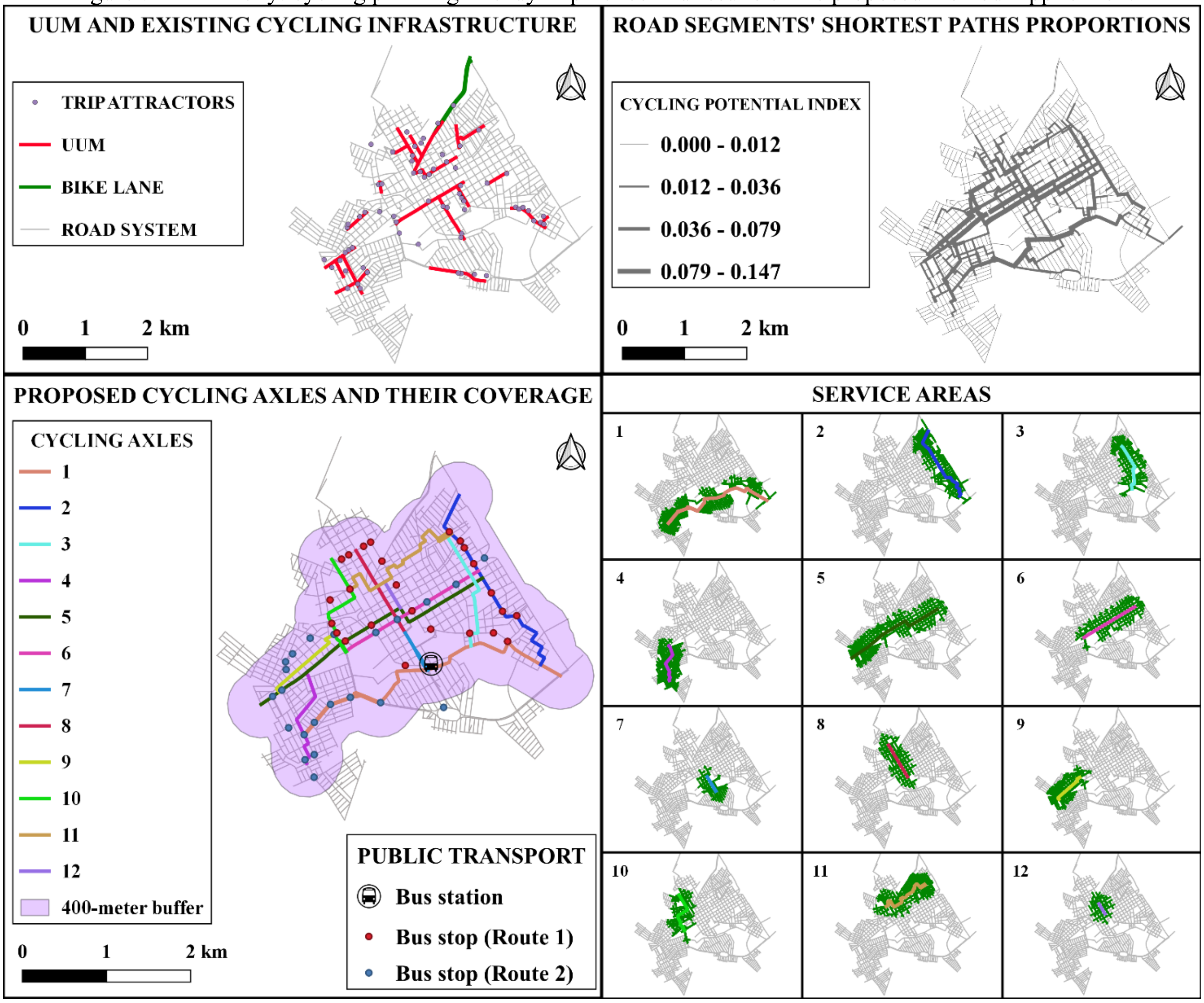
3.1 Cycling planning in Bariri: results and discussion

Figure 5 shows the cycling planning already in practice and the results of the proposed method's application to the city of Bariri. The urban mobility plan prepared for the municipality, regarding active transport, is composed of nine continuous sets of road segments self-titled Minimum Urban Units (or UUM, which in Portuguese stands for *Unidades Urbanísticas Mínimas*), which account for 9.8 km and promote access to 67 of the city's main cycling trip attractors. Regarding the guidelines proposed in this work, the road segments with the greatest cycling potential in the city of Bariri are those whose proportion in the calculated optimal routes is approximately 15% (C=0.147). Approximately 19% of the routes calculated based on the operational quality for cycling are equal to their respective routes that minimize the travel distance and, among those that are not, there is an average percentage deviation of 10.73% in relation to these last.

From the road segments with the greatest cycling potential, continuous cycling axles were proposed in order to connect the main origins and destinations of bicycle trips consistently with the traffic flow directions allowed in the network. As also shown in Figure 5, 12 cycling axles connected to each other were defined for the city of Bariri, totaling 23.3 km in length, which allow round trips to any region of the study area. When compared with the UUM, however, only 3.5 km of this proposed cycling network coincide with the road segments of greatest interest by municipal transportation authorities, suggesting that the latter may not have been selected using technical criteria. Furthermore, the existing bike lanes in the city of Bariri are characterized by a very low cycling potential index, since they are inserted in a way that does not contribute to cyclists in their utilitarian trips, serving only for leisure.

Access to cycling axles through residential roads was verified in terms of their respective service areas, calculated from distances of 400 meters in the network, as shown in Figure 5. It is estimated that 910 network nodes are served by the proposed cycling network. Regarding the study area coverage, 400-meter buffers were defined from each axis, which were crossed with the city's potential cycling demand. It is estimated that the proposed cycling network serves about 95% of these cyclists.

Figure 5 – Bariri city: cycling planning already in practice and results of the proposed method' application.



Source: Authors (2022).

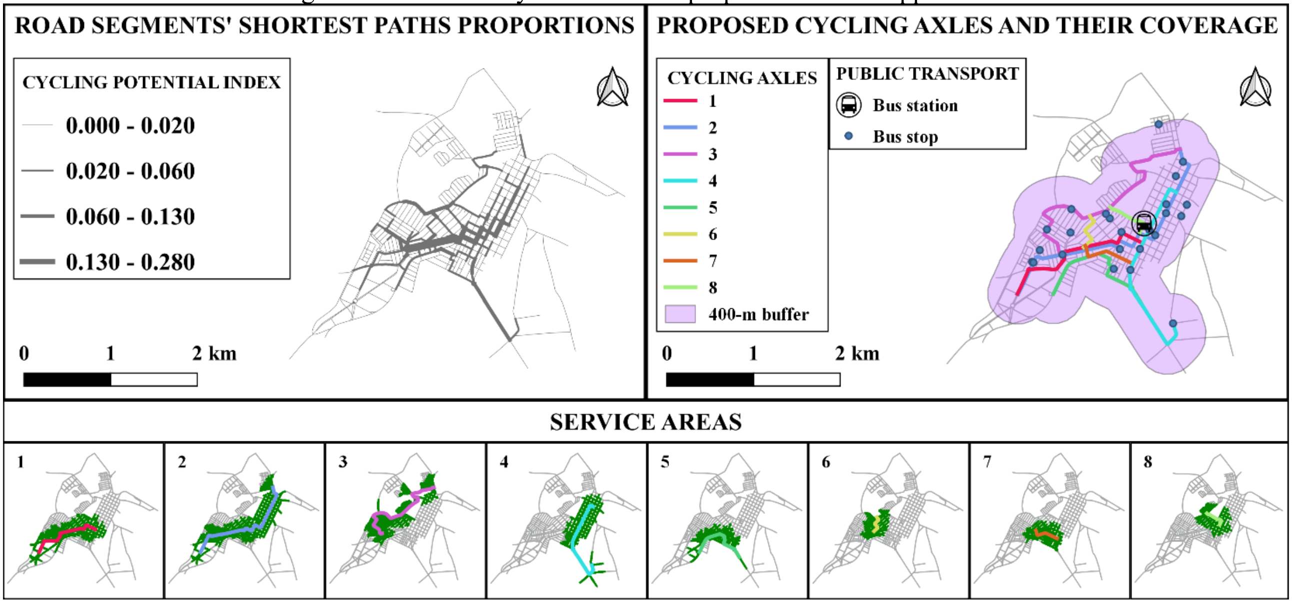
Regarding the potential for integration with public transport, Figure 5 also shows 45 bus stops in the city of Bariri referring to two different bus routes (both with the same end point, that is, a bioenergy company located outside the urban limits of Bariri and whose access is exclusively through a municipal road where cyclists are not allowed), as well as the local bus station, among which 25 elements coincide with the proposed cycling network, and only one is not served by it. On average, the distance to access bus stops that do not coincide with the proposed network from the cycling axles themselves is approximately 147 meters.

3.2 Cycling planning in Bocaina: results and discussion

Figure 6 shows the results of the proposed method's application to the city of Bocaina. It is observed that its road segments with the greatest cycling potential are those whose proportion in the calculated optimal routes is 28% (C=0.280), a higher percentage than that observed in the city of Bariri due to the smaller number of assessed road segments. The more compact road system also reflects in other results: in Bocaina, 29% of the routes calculated based on the operational quality for cycling are equal to their respective routes that minimize the travel distance. Among those that are not, however, there is an average percentage deviation of 8.91% in relation to the minimum distance paths, which is similar to that observed for the city of Bariri.

Analogously, 8 cycling axles were proposed for the city of Bocaina, as shown in Figure 6, totaling 16.3 km in length. Furthermore, 435 network nodes and more than 77% of the city's potential cycling demand are served by the proposed cycling network. However, unlike the results found for the city of Bariri, the proposed cycling network for Bocaina is provided with two road sections (belonging to cycling axles 4 and 5 and whose lengths are, respectively, 956 and 469 meters) classified as LTS4 , due to their functional hierarchy and consequent speed limit. This can be partially explained by the fact that access to many cycling trip attractors in the city is exclusively through these road sections, which, despite being weighted with the worst equivalence factors in the proposed method, remain with large proportions on the optimal routes calculated. Thus, it is suggested that the possibility of inserting bike paths in both road sections be evaluated, totally segregating cyclist traffic from motorized traffic.

Figure 6 – Bocaina city: results of the proposed method' application.



Source: Authors (2022).

Regarding the potential for integration with public transport, Figure 6 also shows 24 bus stops and the bus station in the city of Bocaina, among which 11 elements coincide with the proposed cycling network, and, as for Bariri, only one bus stop is not served by it. On average, the distance to access bus stops that do not coincide with the proposed network from the cycling axles themselves is approximately 70 meters.

4 CONCLUSIONS

This study sought to propose a method to systematize cycling planning in small-sized Brazilian cities based on open data geoprocessing. For this, despite the obvious importance of conducting specific research and field surveys in each Brazilian city for greater reliability of the results, information suggested by other authors regarding the potential cycling demand in these smaller urban centers was used, as well as open data of collaborative mapping, DEM etc. for the characterization of the geometric and operational attributes of the transportation network.

Case studies conducted in the cities of Bariri-SP and Bocaina-SP allowed to exemplify the applicability of the proposed method, from which continuous, accessible, and connected cycling axles were defined for each city. The proper treatment of these axles through traffic calming, adequate vertical and horizontal signage, etc. can contribute to the popularization of cycling in utilitarian trips and to the strengthening of the "bicycle culture" still in force in small-sized Brazilian cities. It is important to highlight that, although the efforts of this work are aimed at the mixed traffic situation, in these cities, the insertion of cycling infrastructure such as bike lanes and bike paths is not discarded, as long as they are strictly required.

Regarding the limitations of the methodology and suggestions for future work, it is proposed that other models for assessing the bicycle level of stress and/or service be considered in the assignment of impedances, preferably those that consider a more complete set of predictor variables, or that changes be proposed to LTS criteria in order to incorporate other stressors to cycling not considered in this work. In addition, it is proposed that weighting factors should also be considered for bicycle travel destinations.

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Authors' contribution

The first author, Marcelo Monari, was responsible for the conceptualization, development of the methodology, formal analysis of the results, writing and editing of the work. The second author, Paulo Cesar Lima Segantine, was also responsible for conceptualizing, as well as supervising and reviewing the work as a whole.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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