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Level of Traffic Stress, Urban Pavement Service Index, and road slope combined for the evaluation of a 5-, 10- or 15-minute Neighborhood

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Level of Traffic Stress, Urban Pavement Service Index, and road slope combined for the evaluation of a 5-, 10- or 15-minute Neighborhood

ABSTRACT
Objective – Develop a road segment quality index by combining LTS, ISU, and road slope to assess the potential of "X-minute neighborhoods" (XmN) from a cycling perspective.
Methodology – The index was applied in a case study conducted in the Cidade Jardim neighborhood (São Carlos-SP, Brazil), involving the georeferencing and scoring of 77 bicycle Trip Attractors (TAs).
Originality/Relevance – Proposes a novel approach to cycling infrastructure assessment integrated with the XmN concept, still underexplored in Brazilian urban contexts.
Results – The neighborhood shows strong potential to become a 10mN or 15mN, despite some poor road conditions.
Theoretical/Methodological Contributions – Introduces a new composite index for evaluating cycling infrastructure, combining key technical variables for urban planning.
Social and Environmental Contributions – Provides input for public policies that promote sustainable transportation and equitable distribution of essential urban services.

KEYWORDS: Cycling. Active Transport. Sustainable Urban Mobility.

Level of Traffic Stress, Índice de Serventia Urbano e declividade viária combinados para a avaliação de uma vizinhança de 5, 10 ou 15 minutos

RESUMO
Objetivo - Desenvolver um índice de qualidade viária combinando LTS, ISU e declividade viária para avaliar o potencial de "vizinhanças de X minutos" (XmN) sob a ótica do ciclismo.
Metodologia - Aplicação do índice em um estudo de caso no bairro Cidade Jardim (São Carlos-SP, Brasil), com georreferenciamento e pontuação de 77 Polos Geradores de Viagens (PGVs).
Originalidade/relevância - Propõe uma abordagem inédita de avaliação cicloviária integrada ao conceito de XmN, ainda pouco explorado no contexto urbano brasileiro.
Resultados - O bairro apresenta alto potencial para se tornar uma 10mN ou 15mN ciclável, apesar da precariedade de parte da infraestrutura viária.
Contribuições teóricas/metodológicas - Introduz um novo índice composto para análise da qualidade cicloviária, combinando variáveis técnicas relevantes para o planejamento urbano.
Contribuições sociais e ambientais - Oferece subsídios para políticas públicas que incentivem o transporte sustentável e a distribuição equitativa de serviços urbanos essenciais.

PALAVRAS-CHAVE: Transporte Cicloviário. Transporte Ativo. Mobilidade Urbana Sustentável.

Nivel de Estrés De Tránsito, Índice de Servicio Urbano y pendiente de la carretera combinados para la evaluación de un barrio de 5, 10 o 15 minutos

RESUMEN
Objetivo – Desarrollar un índice de calidad de segmentos viales combinando LTS, ISU y pendiente de las calles, para evaluar la viabilidad de los "barrios de X minutos" (XmN) desde la perspectiva del ciclismo.
Metodología – El índice fue aplicado en un estudio de caso en el barrio Cidade Jardim (São Carlos-SP, Brasil), que involucró la georreferenciación y puntuación de 77 Puntos Generadores de Viajes (PGVs) por bicicleta.
Originalidad/Relevancia – Propone un enfoque novedoso para la evaluación de la infraestructura ciclista, integrado con el concepto de XmN, aún poco explorado en contextos urbanos brasileños.

Resultados – El barrio muestra un gran potencial para convertirse en una 10mN o 15mN, a pesar de algunas condiciones viales deficientes.
Contribuciones Teóricas/Metodológicas – Introduce un nuevo índice compuesto para evaluar la infraestructura ciclista, combinando variables técnicas clave para la planificación urbana.
Contribuciones Sociales y Ambientales – Aporta insumos para políticas públicas que promuevan el transporte sostenible y la distribución equitativa de servicios urbanos esenciales.

PALABRAS CLAVE: Transporte en Bicicleta. Transporte Activo. Movilidad Urbana Sostenible.

1 INTRODUCTION AND BACKGROUND

In recent years, bicycle use has grown significantly in cities worldwide. The popularization of this mode of transportation is due to several factors, such as the pursuit of a healthier and more sustainable lifestyle, alongside its ease of access and maintenance compared to private motorized vehicles (Valenzuela *et al.*, 2024, p. 420).

In Brazil, in light of the need to make urban mobility more accessible, sustainable, safe, and efficient, the Brazilian National Urban Mobility Policy (PNMU – *Política Nacional de Mobilidade Urbana*) was established in 2012 through Law No. 12,587, whose main guideline is the promotion of active and collective modes of transport over individual motorized vehicles (Brazil, 2012, p. 1). Years later, in 2018, the Brazilian Bicycle Program (PBB – *Programa Bicicleta Brasil*) was established through Law No. 13,724, which aims to specifically encourage bicycle transportation across the national territory (Brazil, 2018, p. 1). Therefore, in theory, when aligned with the PNMU – especially in cities with more than 20,000 inhabitants – the PBB can promote the integration of cycling with other modes of transport and assist in infrastructure planning for active mobility.

Despite the aforementioned legal efforts, there is still much discussion about the lack of technical support to assist in decision-making regarding the allocation of cycling infrastructure in Brazil (Monari, 2022, p. 31). While the benefits of widespread bicycle use are well-known (such as contributions to public health and reduced space requirements), this shortage of technical decision-support tools prevents the vast majority of Brazilian cities from adopting smart and rational urban planning models, such as that based on the "X-minute neighborhood" (XmN) concept (e.g., 5mN, 10mN, and 15mN).

The XmN concept is not new, but it gained prominence during the COVID-19 pandemic in 2020, when cities worldwide had to deploy rapid, efficient solutions to resume daily activities while complying with sanitary barriers and health recommendations (C40 Cities Climate Leadership Group, 2020). In short, an XmN is a self-sufficient territorial unit that contributes to reducing dependence on individual motorized vehicles (Moreno *et al.*, 2021, p. 100). Globally, it is estimated that more than one hundred cities are implementing this concept, but only two of them are located in Latin America: Buenos Aires (Argentina) and Bogotá (Colombia) (Teixeira *et al.*, 2024, p. 10).

According to Santos and Santos (2022, p. 115), urban mobility planning in Brazilian cities directly reflects State interests, and planning models have historically emphasized individual motorized transport. This relegates active transportation modes, such as cycling and walking, to a secondary status, even though they are widely used in Brazil, particularly in small cities (ANTP, 2020, p. 9). In this context, the XmN concept can help reverse this situation by decentralizing urban functions and services (Bocca *et al.*, 2021, p. 400; Ferrer-Ortiz *et al.*, 2022, p. 147) and encouraging active transportation for short trips.

Although the concept of XmN is still poorly systematized for large-scale application (Kamruzzaman, 2022, p. 1), successful international examples suggest that one of its pillars is the promotion of spatial accessibility to Trip Attractors (TAs), that is, the ease of reaching everyday travel destinations (Lu; Diab, 2023, p. 2). In Italy, for example, Abdelfattah, Deponte, and Fossa (2022) found that residents of central Milan have easy access to essential services on foot, unlike those residing in the outer neighborhoods of the city. Similar results were also observed in Rome, which, despite its historic center being designated a UNESCO World Heritage Site, still experiences peripheral urban growth that highlights economic and socio-spatial inequalities (Chiaradia *et al.*, 2024). Likewise, in Naples, more remote regions lack essential services, consequently forcing residents to rely heavily on public transport or private automobiles (Gaglione *et al.*, 2022).

The failure to systematize the application of the XmN concept so far is due to the difficulty in developing a universal approach (Khavarian-Garmsir; Sharifi; Sadeghi, 2023, p. 3). This was evidenced by Teixeira *et al.* (2024, p. 13), who explored various perspectives of the concept across distinct realities. For example, while the urban mobility plan in Tucson (USA) emphasized travel time, Surrey (Canada) focused on transportation quality and safety, and Oslo (Norway) prioritized land use. Based on the documents analyzed, the authors classified the cities into *innovators*, *early adopters*, *early majority*, *late majority*, and *laggards*. The first group consists of cities already advanced in the transition to the XmN model, such as Paris (France), Melbourne (Australia), and Barcelona (Spain). Early adopters, such as the aforementioned Milan (Italy), possess well-developed plans to implement the concept. Oslo (Norway), classified as part of the early majority, remains in the initial stages of implementing 15mN elements. Among the cities analyzed, 41% were classified as late majority, indicating minimal effort in their action plans. Finally, approximately 13% were identified as laggards, which are cities that have not yet adopted any practices of the concept within their planning models but have expressed interest in transitioning from the conventional model to the XmN framework.

The specific application of the 15mN concept in the urban mobility planning of European cities, such as Munich (Germany), Madrid (Spain), Ghent (Belgium), and Amsterdam (Netherlands), has helped the local economy, creating jobs at the neighborhood level and fostering a sense of security and belonging among their residents. However, authors such as Büttner *et al.* (2024, p. 8) warn of the need to implement this model carefully and through region-specific studies, to prevent potential gentrification issues. Thus, there is a pressing demand for initiating similar studies in emerging countries as well, rather than directly adopting foreign frameworks.

In Brazil, despite the well-known shortage of data for transportation planning, many cutting-edge techniques extensively documented in the literature can serve as technical support for the promotion of XmNs, especially those associated with cycling. An example is the Level of Traffic Stress (LTS) classification (Mekuria; Furth; Nixon, 2012), which aims to quantify a cyclist's stress level based on speed limits and the number of traffic lanes on a scale of 1 to 4, representing the best and worst cases, respectively.

The LTS classification has already been adopted to determine the centrality of road segments and the resulting priority levels for investment in cycling routes in Brazil (Monari *et al.*, 2024), as well as to compare theoretical stress levels with those measured in the field through physiological stress measurements of cyclists in a medium-sized city (Miranda *et al.*, 2018). In the latter case, although the study did not find a strong correlation between the variables analyzed, the international literature advocates complementing the original classification with additional stress variables, such as steep slopes (Rybarczyk *et al.*, 2020, p. 90) and poor pavement conditions (Zeile *et al.*, 2016, p. 211).

Against this backdrop, the assessment of urban pavement surface conditions can also be based on simplified techniques that facilitate large-scale application, such as the Urban

Pavement Service Index (ISU – *Índice de Serventia Urbano*) (Villibor *et al.*, 2009). Furthermore, the wide range of free Digital Elevation Models (DEMs) developed in recent decades, such as the TOPODATA DEM (INPE, 2008), has facilitated the inclusion of altimetric variables in Geographic Information System (GIS) routing algorithms. This integration is fundamental for infrastructure planning for active transport, since walking and cycling are strongly influenced by topographic conditions (Winters *et al.*, 2010, p. 7).

2 OBJECTIVES

The objective of this study is to combine key influencing variables on bicycle use – namely LTS, ISU, and road slope – into a cyclability index to evaluate the adherence of spatial units to the XmN concept. To demonstrate the proposed approach, a case study was conducted in the Cidade Jardim neighborhood of São Carlos, SP, Brazil.

3 METHOD

The following section presents the research materials and methods, which comprise: 1) GIS software for spatial data geoprocessing; 2) classification criteria for LTS in mixed traffic; 3) ISU assessment parameters; 4) frameworks for evaluating the influence of road slopes on cycling; 5) estimation of the cyclability index for road segments; 6) evaluation and mapping of 5mN, 10mN, and 15mN conditions within a given spatial unit; and 7) case study data.

3.1 Geographic Information System (GIS)

As briefly noted in the introduction, GIS software is essential to any approach aiming to evaluate and/or plan the XmN concept, given that spatial data are strictly required for this purpose. Therefore, this study was carried out using an open-source GIS, namely QGIS (version 3.34.12). Among other advantages, this software features native plugins for transport network analysis, allowing, for example, the batch-processed identification of shortest paths between user-specified origin-destination (*ij*) pairs based on various criteria.

3.2 LTS classification

Table 1 presents the criteria for LTS classification of road segments in mixed traffic, where space is shared between bicycles and automobiles. This classification relies on three predictive variables: the number of traffic lanes, the posted speed limit, and the presence of centerlines separating traffic directions (Mekuria; Furth; Nixon, 2012, p. 37).

Table 1 - LTS classification for mixed traffic

Speed limit (km/h)	Number of traffic lanes		
	2-3	4-5	≥ 6
Up to 40	1 or 2*	3	4
50	2 or 3*	4	4
60 or higher	4	4	4

Source: Mekuria, Furth, and Nixon (2012, p. 37).
*Lower value is assigned to road segments without a marked centerline or to residential streets with fewer than 3 lanes; higher value is assigned otherwise.

It is worth noting that while the original criteria for LTS classification also include bike lanes and intersections, these situations were excluded from this study due to the absence of dedicated cycling infrastructure within the study area and the low geometric complexity of the evaluated intersections.

3.3 ISU assessment

The ISU is calculated by weighting characteristic urban pavement defects based on their type (patching, potholes/shoving, and cracking, each assigned a specific factor – *F*, according to Table 2) and degree of deterioration (*G*). The latter is derived from the affected area (*A*) and severity (*S*) of each defect, as shown in Table 3 (Villibor *et al.*, 2009, p. 174-176).

Table 2 - Weighting factor related to the defect type (*F*)

Defect type	Weighting factor (*F*)
Patching	3
Potholes / Shoving	2
Cracking	5

Source: Villibor *et al*. (2009, p. 175).

Table 3 - Deterioration degree of the urban pavement (*G*)

Severity	Affected area		
	$A_1 \leq 10\%$ (Localized)	$10\% < A_2 < 50\%$ (Distributed)	$A_3 \geq 50\%$ (Widespread)
S_1 (Low)	1	2	3
S_2 (Medium)	2	4	6
S_3 (High)	3	6	9

Source: Villibor *et al*. (2009, p. 174).

Once the degree of deterioration (*G*) for each type of defect has been determined through field surveys, the ISU can be calculated using Equation (1). The pavement condition based on the ISU value is presented in Table 4.

$$ISU = 100 - \left[\frac{100}{90} \times (G_P \times F_P + G_{PS} \times F_{PS} + G_C \times F_C)\right] \quad (1)$$

Where G_P, G_{PS}, and G_C are the deterioration degrees of the urban pavement associated with patching, potholes/shoving, and cracking, respectively; and F_P, F_{PS}, and F_C are the weighting factors for the assessed pavement defects, in that same order.

Table 4 - Pavement condition based on the ISU

Pavement condition	ISU
Very poor	0 a 30
Poor	30 a 45
Moderate	45 a 70
Good	70 a 80
Very good	80 a 100

Source: Villibor *et al*. (2009, p. 175).

3.4 Road slopes

Ideal road slopes for cycling are limited to 3%, with a maximum value of 5% allowable during the design phase. Above this threshold, steep uphill slopes demand significant energy expenditure from cyclists, while steep downhill slopes compromise safety (Austroads, 2014, p. 95). However, the topographical conditions of a given city or region of study do not always allow the selection of cycling routes with grades restricted to those values. Thus, several technical manuals propose maximum acceptable grade lengths to be incorporated into the design, as exemplified in Table 5 (AASHTO, 1999, p. 39).

Table 5 - Grade thresholds for shared-use paths

Road slope (%)	Acceptable grade length – L_{grade} (m)
5-6	240
7	120
8	90
9	60
10	30
> 10	15

Source: AASHTO (1999, p. 39).

3.5 Road segment cyclability index

To combine the three quantitative variables detailed above into a road segment cyclability index ($I_{cyclability}$), the following hypotheses were adopted in this study: 1) all key variables have the same degree of influence on both bicycle mode choice and cyclists' route selection; and 2) in order to standardize the evaluation, each variable has 4 intervals of geometric and/or operational quality (analogous to the intervals of the LTS classification), as presented in Table 6. After applying the criteria in Table 6, $I_{cyclability}$ is obtained by the arithmetic mean of the individual evaluations of each influencing variable, according to Equation (2). The interpretation for each index interval is presented in Table 7.

Table 6 - Geometric and/or operational quality of road segments for cycling

Classification	Influencing variable		
(I_{LTS}, I_{ISU}, and I_{slope})	LTS	ISU	Road slope (%)
1	1	81 - 100	< 3%
2	2	71 - 80	3-5%
3	3	46 - 70	> 5% and $L_{act} \leq L_{grade}$
4	4	0 - 45	> 5% and $L_{act} > L_{grade}$

Source: Authors (2025).

$$I_{cyclability} = \frac{I_{LTS} + I_{ISU} + I_{slope}}{3} \quad (2)$$

Where I_{LTS}, I_{ISU}, and I_{slope} are the standardized individual assessments for LTS, ISU, and road slope, respectively.

Table 7 - Interpretation of the $I_{cyclability}$

$I_{cyclability}$	Interpretation
1.00 – 2.00	Road segment with good geometric and/or operational quality, recommended for cycling routes. Occasional interventions or modifications may be required.
2.01 – 3.00	Road segment with intermediate geometric and/or operational quality. Significant interventions and modifications in at least one of the evaluated criteria may be required for incorporation into cycling routes.
3.01 – 4.00	Road segment with low geometric and/or operational quality, not recommended for cycling routes in its current state. Severe interventions and modifications are required in more than one of the evaluated criteria.

Source: Authors (2025).

3.6 Assessment and mapping of the 5mN, 10mN, and 15mN conditions

The proposed approach for evaluating and mapping the 5mN, 10mN, and 15mN conditions relies on the previously estimated cyclability index ($I_{cyclability}$) for each road segment. Mapping one or more of these conditions may be omitted if uniform accessibility levels are observed across the study area due to local characteristics.

First, the TAs consistent with the XmN concept are mapped and weighted according to the scoring system in Table 8, which was adapted from McNeil (2011, p. 58). In short, this system incorporates a comprehensive set of non-work-related TAs (nutrition, education, recreation and commerce, health and aesthetics, public transport, and other services). Furthermore, it accounts for both the relative importance of different TA categories and the specific number of occurrences required for each type-*k* TA to effectively satisfy the resident population.

Table 8 - Scoring system for weighting TAs

TA category	TA type (*k*)	Points per occurrence (p_k)	Maximum occurrences	Total points (T_k)
Nutrition	Supermarket and full grocery store (*1*)	5.000	2	10.000
	Coffee shop and snack bar (*2*)	1.250	4	5.000
	Restaurant (*3*)	0.625	12	7.500
	Bakery, fruit and vegetable shop, and butcher shop (*4*)	0.625	8	5.000
Education	Middle School (public only) (*5*)	10.000	1	10.000
	High School (public only) (*6*)	10.000	1	10.000
Recreation and commerce	Park, square, and open public space (*7*)	10.000	1	10.000
	Sports club, theater, movie theater, etc. (*8*)	1.500	5	7.500
	Clothing store (*9*)	1.250	4	5.000
Health and aesthetics	Primary Health Care (PHC) center (*10*)	10.000	1	10.000
	Drugstore (*11*)	1.250	2	2.500
	Gym (*12*)	2.500	2	5.000
	Beauty salon, hairdresser, etc. (*13*)	0.625	4	2.500
Public transport	Bus stop (*14*)	1.250	4	5.000
Service	Post office (*15*)	2.500	1	2.500
	Bank (*16*)	1.250	2	2.500
Total	-	-	-	100

Source: Adapted from McNeil (2011, p. 58).

Next, the shortest paths between all origin-destination (*ij*) pairs within the study area are calculated. For this purpose, the graph nodes (representing dead-ends and intersections) comprise the set of origins (*O*), while the georeferenced TAs constitute the set of destinations (*J*). Thus, based on the criterion of minimizing travel impedance between a given *ij* pair, the impedance assignment strategy defined by Equation (3) is applied to calculate the cycling routes.

Finally, the accessibility index of each origin $i \in O$, representing the XmN condition, is computed using Equations (4) and (5), and subsequently interpolated across the entire study region. To determine whether a type-*k* TA is accessible within X minutes from origin *i*, Equations (6) and (7) are applied using the cycling speeds specified in Table 9.

$$L_{eq_e} = L_{act_e} \times I_{cyclability} \tag{3}$$

$$A_i = \frac{\sum_{k=1}^{16} P_{ik}}{100} \tag{4}$$

$$P_{ik} = \text{minimum}\{p_k \times n_{ik}; T_k\} \tag{5}$$

$$t_{ij} = \sum_{e=1}^{m} \frac{\sigma_{ij}(e) * L_{act_e}}{V_e} \tag{6}$$

$$\sigma_{ij}(e) = \{1, \text{if } e \text{ is used in } \sigma_{ij}; 0, \text{otherwise}\} \tag{7}$$

Where L_{eq_e} and L_{act_e} are the equivalent and actual lengths of the road segment *e*, respectively; P_{ik} are the points assigned to TA type *k*, from origin *i*; p_k is the score associated with a single occurrence of TA type *k*; n_{ik} is the number of TAs type *k* accessible from *i* within X

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minutes; T_k is the limit of points that can be assigned to a TA type k; σ_{ij} and t_{ij} are the shortest path and cycling travel time between i and j, respectively; V_e is the expected cycling speed along road segment e, which depends on the road slope and the direction of traffic flow along the segment to reach destination j; e m is the number of network segments.

Table 9 - Cyclist speeds under the influence of different road slopes

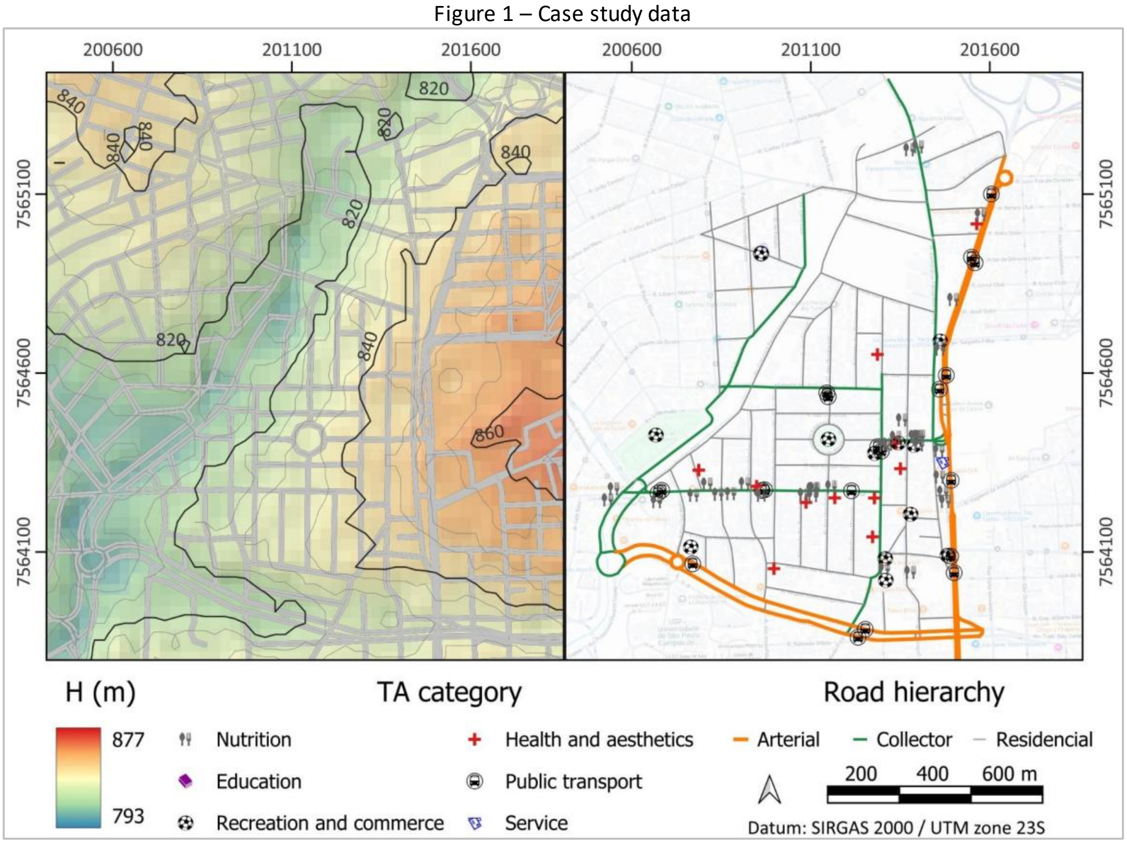
Road slope (%)	Uphill speed – V (km/h)	Downhill speed – V (km/h)
< 3%	24	24
3-5%	16	32
> 5%	8	40

Source: Monari, Segantine, and Silva (2022, p. 697).

3.7 Case study data

Figure 1 presents the case study data. The left map shows the TOPODATA DEM (INPE, 2008) of the Cidade Jardim neighborhood in São Carlos-SP (Brazil), while the right map shows the TAs within the study area, georeferenced and categorized through field surveys. The graph representing the local road system, also shown on the right map, was built from vector layers extracted from the OpenStreetMap (OSM) collaborative mapping platform. Road hierarchy was subsequently assigned to each segment based on the Urban Mobility Plan of São Carlos-SP (São Carlos City Hall, 2023, p. 15).

Figure 1 – Case study data



Source: Adapted by the authors from INPE (2008), IBGE (2022), and São Carlos City Hall (2023, p. 15).

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The neighborhood is predominantly residential and, according to the latest Brazilian Demographic Census (IBGE, 2022), has an estimated population of 3,456 inhabitants. Its terrain is primarily characterized as gently undulating (EMBRAPA, 1979), with 65% of the total area exhibiting slopes between 3% and 8%. Such topography offers a compelling case study for cycling planning.

Regarding the road hierarchy, the neighborhood is bordered to the south and east by arterial roads (Av. Trabalhador Sãocarlense and Av. São Carlos, respectively) and is intersected by collector roads, most notably Alameda dos Crisântemos – the one in Figure 1 that concentrates the largest number of TAs.

In total, 77 TAs consistent with the XmN framework were identified in the study area. Of these, 33 belong to the nutrition category; 12 to recreation and commerce; 11 to health and aesthetics; 20 to public transport (bus stops); and only 1 to other services (a post office). No education-related TAs were identified within the neighborhood. Furthermore, regarding the health and aesthetics category, no Primary Health Care (PHC) centers are located within the immediate surroundings of the Cidade Jardim neighborhood. Finally, the field surveys conducted for TA georeferencing and categorization served a dual purpose, as they were also used to collect the predictor variables for both the LTS classification and the ISU assessment, as illustrated in Figure 2.

Figure 2 – Photographic record of field surveys

Source: Authors (2025).

4 RESULTS AND DISCUSSION

Figures 3 and 4 summarize the case study results, presenting the frequency distribution of bicycle travel times to TAs, and the mapping of the LTS classification, ISU assessment, and road slopes, as well as the cyclability index and spatial accessibility for a 5mN, respectively.

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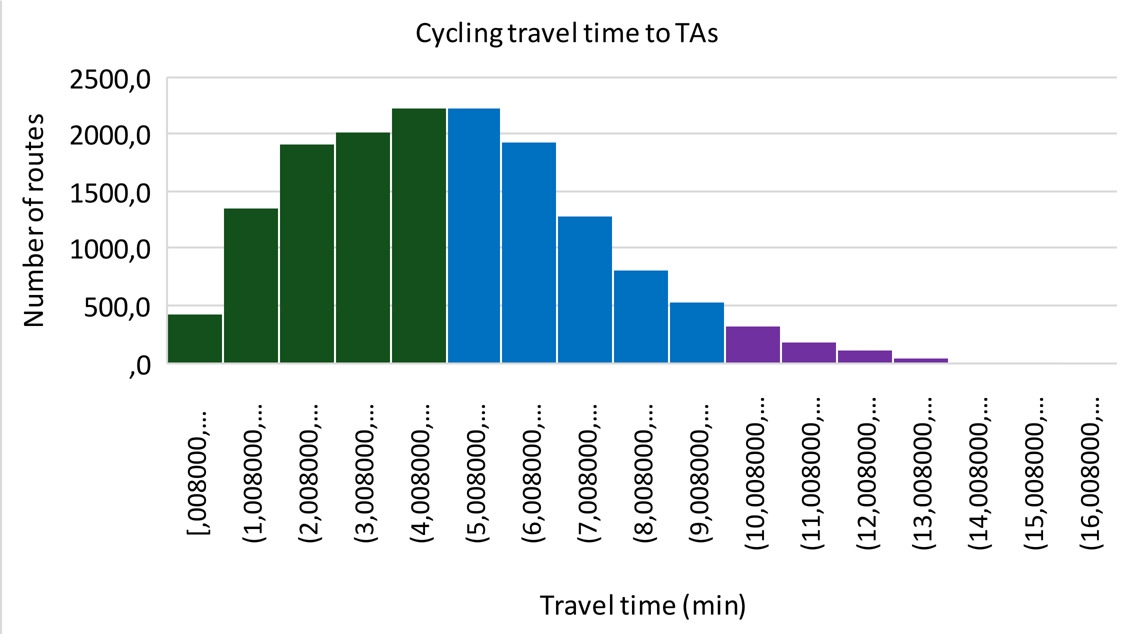
In total, 15,477 cycling routes were calculated within the study area (201 graph nodes as origins x 77 TAs as destinations) via batch processing in QGIS. Among these, 99.91% are within a 15-minute travel time (represented in green, blue, and purple in Figure 3), 95.43% are within 10 minutes (blue and purple), and 51.33% are limited to 5 minutes (purple only). This frequency distribution highlights the strong potential of the Cidade Jardim neighborhood to function as a 15- or 10-minute cycling neighborhood. Despite containing road segments with poor cyclability, which force systematic detours from the routes that minimize travel distance, access to local TAs remains guaranteed within a maximum 15-minute bike ride. Currently, however, not all TAs essential to the 15mN framework are present within the study area, resulting in intermediate levels of accessibility.

The upper maps in Figure 4 present the individual assessments of the variables influencing bicycle use, while the lower maps display the spatial distribution of the $I_{cyclability}$ and the 5mN threshold within the study area. In the latter case, mapping the remaining temporal thresholds (10mN and 15mN) is redundant, as nearly all routes within these travel times yield homogeneous accessibility levels across the entire neighborhood.

Notably, only the arterial roads and a section of a collector road (Av. Francisco Pereira Lopes) within the study area are classified as LTS 3 or 4 due to their speed limits. This indicates potential inconsistencies in the Urban Mobility Plan regarding the hierarchical classification of that collector road. The other collector roads classified as LTS 2 are those with marked centerlines.

Figure 3 – Frequency distribution of access times to bicycle TAs



Source: Authors (2025).

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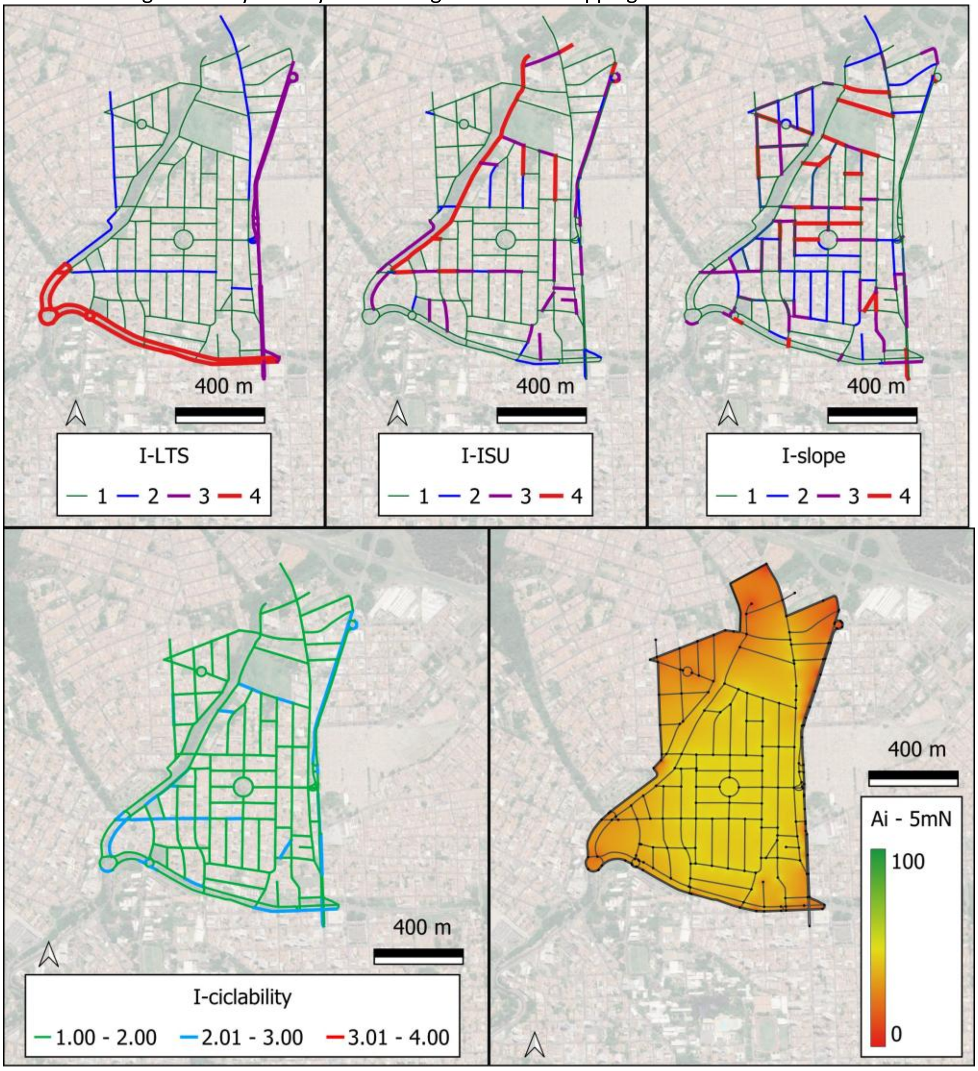
Figure 4 – Cyclability of road segments and mapping of the 5mN condition



Source: Authors (2025).

Regarding the ISU, 49 road segments (16.78%) within the neighborhood exhibit pavement conditions ranging from regular to very poor, including unpaved segments in extreme cases. As for road slopes, an asymmetric directional analysis is required: since a two-way segment can be traveled either uphill or downhill, its geometric quality assessment varies by direction. Nonetheless, 80 segments (27.40%) are estimated to have slopes steeper than 5%.

Regarding the overall cyclability of the network system, the arithmetic mean of the individual evaluations resulted in $I_{cyclability}$ values that are consistently limited to 3.00. This indicates that while some network segments are heavily penalized by a specific parameter, their deficiencies are isolated, meaning no segment requires severe interventions in more than one criterion.

Finally, regarding the accessibility indices (ranging from 0 to 100) consistent with the XmN framework, the following values were observed for the Cidade Jardim neighborhood: a homogeneous index of 51.25 throughout the study area for a 15mN; values between 36.25 and 51.25 for a 10mN (which results in visual variations imperceptible in the mapping); and indices ranging from 1.25 to 51.25 for a 5mN. In the latter case, as illustrated in Figure 4, higher accessibility is concentrated in the central region of the neighborhood, whereas severely limited accessibility occurs in the peripheral areas (particularly in the northern portion). This spatial pattern aligns with previous findings reported in the introductory section.

5 FINAL CONSIDERATIONS

This study sought to combine three variables influencing bicycle use – LTS, ISU, and road slope – into a road segment cyclability index, subsequently applying this index as an evaluation criterion within a multi-distance accessibility framework. The case study, conducted in a neighborhood of a medium-sized Brazilian city, demonstrated the applicability of the proposed approach and highlighted its strengths, including the straightforward visual and numerical interpretation of the results and the minimal requirement for input variables, which can be easily collected in the field.

Pragmatically, the $I_{cyclability}$ values being limited to 3.00 throughout the studied neighborhood reflect an optimistic outlook. However, none of the research method's input variables account for motorized traffic flow to assess the operational quality of cycling routes. Therefore, care must be taken to complement the proposed approach with methods and techniques that address this variable, such as the more recent versions of the LTS classification (Furth; Mekuria; Nixon, 2016).

Ultimately, the Cidade Jardim neighborhood demonstrates the potential to function as a 15-minute cycling neighborhood, as all existing TAs are accessible within a 15-minute bike ride. However, not all the TAs required to fulfill this framework are currently present within the neighborhood. Consequently, these findings offer a valuable starting point for municipal authorities to plan the provision of public services – such as schools and health centers – since, despite being largely consolidated, the neighborhood still contains vacant urban lots available for development.

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STATEMENTS

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CONFLICT OF INTEREST STATEMENT

We, Gabriella Mie Hanada Kodama and Marcelo Monari, declare that the manuscript entitled "Level of Traffic Stress, Urban Pavement Service Index, and road slope combined for the evaluation of a 5-, 10- or 15-minute Neighborhood":

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