

## **Assessing urban infrastructure and access to essential services for active mobility: development of the SIUMA index**

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## **Avaliação da infraestrutura urbana e do acesso a serviços essenciais para mobilidade ativa: desenvolvimento do índice SIUMA**

### **RESUMO**

**Objetivo** - Apresentar a construção conceitual e metodológica do índice de Serviços de Infraestrutura Urbana para os Modos Ativos (SIUMA), desenvolvido para avaliar, de forma integrada, a infraestrutura urbana destinada aos deslocamentos a pé e de bicicleta em relação ao acesso aos serviços essenciais, com foco especial em municípios com até 100 mil habitantes.

**Metodologia** - O estudo foi conduzido por meio de revisão sistemática da literatura nacional e internacional, categorização dos indicadores mais recorrentes, consulta a especialistas e profissionais da área e verificação da disponibilidade de informações em bases de dados públicas. A ponderação dos domínios, temas e indicadores foi realizada pelo método Structured Pairwise Comparison, resultando na definição da estrutura final do índice, calculado exclusivamente com dados públicos e técnicas de geoprocessamento.

**Originalidade/relevância** - O estudo é realizado com base em oportunidades identificadas na literatura quanto à integração entre infraestrutura urbana e acesso a serviços essenciais, bem como quanto à viabilidade operacional e à replicabilidade de instrumentos avaliativos, especialmente em cidades com até 100 mil habitantes.

**Resultados** - O SIUMA foi estruturado a partir de 14 indicadores distribuídos em três domínios principais, constituindo um instrumento metodológico prático, transparente, replicável e de baixo custo, apto a avaliar de forma integrada as condições urbanas para a mobilidade ativa.

**Contribuições teóricas/metodológicas** - O estudo avança ao propor um índice integrado que articula infraestrutura urbana e acesso a serviços essenciais, utilizando metodologia estruturada de ponderação e dados públicos, o que amplia a aplicabilidade e a comparabilidade entre diferentes contextos urbanos.

**Contribuições sociais e ambientais** - O SIUMA oferece subsídios para diagnósticos urbanos e para o planejamento da mobilidade ativa, contribuindo para o fortalecimento da resiliência urbana e, para a melhoria do acesso equitativo a serviços essenciais, sobretudo em municípios com até 100 mil habitantes.

**PALAVRAS-CHAVE:** Mobilidade ativa. Infraestrutura urbana. Serviços essenciais. Indicadores urbanos. Planejamento urbano.

## **Assessing urban infrastructure and access to essential services for active mobility: development of the SIUMA index**

### **ABSTRACT**

**Objective** – To present the conceptual and methodological development of the Urban Infrastructure Services for Active Modes Index (SIUMA), designed to integratively assess urban infrastructure for walking and cycling in relation to access to essential services, with particular focus on municipalities with up to 100,000 inhabitants.

**Methodology** – The study was conducted through a systematic review of national and international literature, categorization of the most recurrent indicators, consultation with experts and professionals in the field, and verification of data availability in public databases. The weighting of domains, themes, and indicators was carried out using the Structured Pairwise Comparison method, resulting in the final structure of the index, calculated exclusively with public data and geoprocessing techniques.

**Originality/Relevance** – The study is based on opportunities identified in the literature regarding the integration between urban infrastructure and access to essential services, as well as the operational feasibility and replicability of assessment instruments, especially in cities with up to 100,000 inhabitants.

**Results** – SIUMA was structured based on 14 indicators distributed across three main domains, constituting a practical, transparent, replicable, and low-cost methodological tool capable of integratively assessing urban conditions for active mobility.

**Theoretical/Methodological Contributions** – The study advances knowledge by proposing an integrated index that articulates urban infrastructure and access to essential services, using a structured weighting methodology and public data, thereby expanding applicability and comparability across different urban contexts.

**Social and Environmental Contributions** – SIUMA provides support for urban diagnostics and active mobility planning, contributing to the strengthening of urban resilience and to improving equitable access to essential services, particularly in municipalities with up to 100,000 inhabitants.

**KEYWORDS:** Active mobility. Urban infrastructure. Essential services. Urban indicators. Urban planning.

## Evaluación de la infraestructura urbana y del acceso a servicios esenciales para la movilidad cativa: desarrollo del índice SIUMA

### RESUMEN

**Objetivo** – Presentar la construcción conceptual y metodológica del índice de Servicios de Infraestructura Urbana para los Modos Activos (SIUMA), desarrollado para evaluar de forma integrada la infraestructura urbana destinada a los desplazamientos a pie y en bicicleta en relación con el acceso a los servicios esenciales, con especial énfasis en municipios de hasta 100.000 habitantes.

**Metodología** – El estudio se llevó a cabo mediante una revisión sistemática de la literatura nacional e internacional, la categorización de los indicadores más recurrentes, la consulta a especialistas y profesionales del área y la verificación de la disponibilidad de información en bases de datos públicas. La ponderación de los dominios, temas e indicadores se realizó mediante el método Structured Pairwise Comparison, lo que dio lugar a la definición de la estructura final del índice, calculado exclusivamente con datos públicos y técnicas de geoprocésamiento.

**Originalidad/Relevancia** – El estudio se basa en oportunidades identificadas en la literatura respecto a la integración entre infraestructura urbana y acceso a servicios esenciales, así como a la viabilidad operativa y la replicabilidad de instrumentos de evaluación, especialmente en ciudades de hasta 100.000 habitantes.

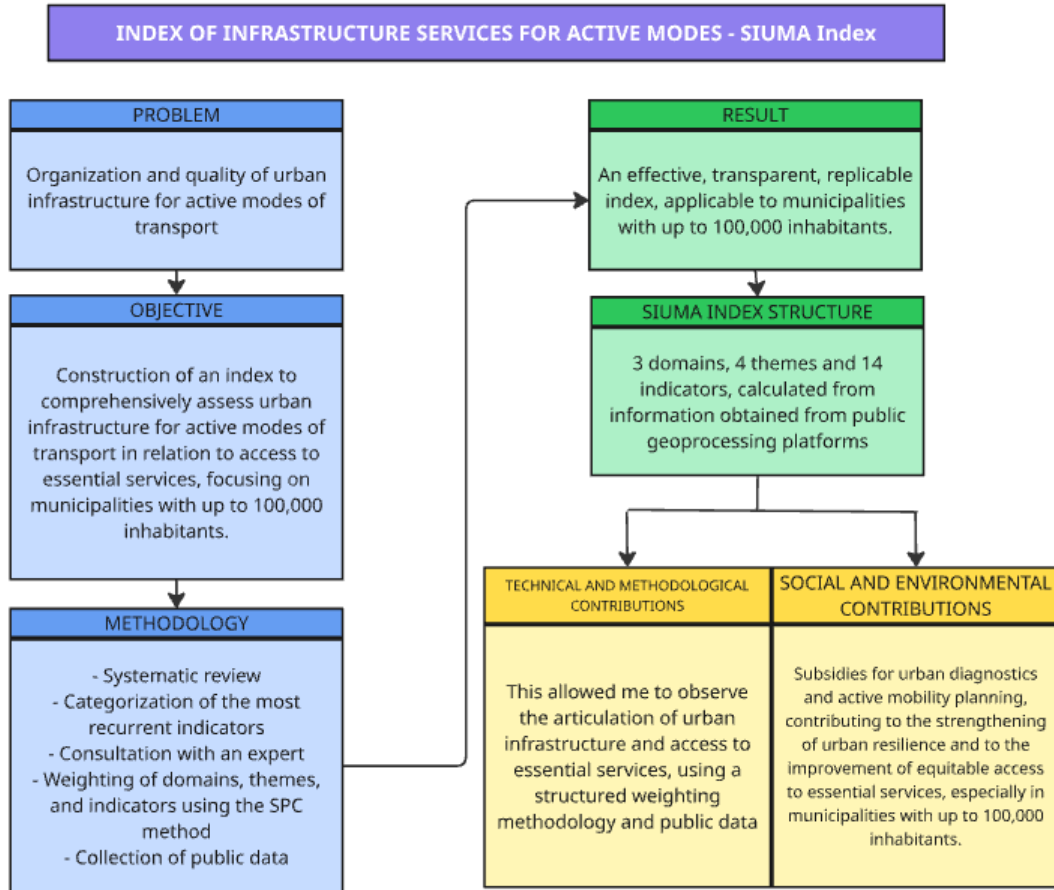
**Resultados** – El SIUMA se estructuró a partir de 14 indicadores distribuidos en tres dominios principales, constituyendo un instrumento metodológico práctico, transparente, replicable y de bajo costo, apto para evaluar de forma integrada las condiciones urbanas para la movilidad activa.

**Contribuciones Teóricas/Metodológicas** – El estudio avanza al proponer un índice integrado que articula infraestructura urbana y acceso a servicios esenciales, utilizando una metodología estructurada de ponderación y datos públicos, lo que amplía la aplicabilidad y la comparabilidad entre diferentes contextos urbanos.

**Contribuciones Sociales y Ambientales** – El SIUMA ofrece insumos para diagnósticos urbanos y para la planificación de la movilidad activa, contribuyendo al fortalecimiento de la resiliencia urbana y a la mejora del acceso equitativo a servicios esenciales, especialmente en municipios de hasta 100.000 habitantes.

**PALABRAS CLAVE:** Movilidad activa. Infraestructura urbana. Servicios esenciales. Indicadores urbanos. Planificación urbana.

**GRAPHICAL ABSTRACT**



## 1. INTRODUCTION

Urban mobility can be understood as the set of movements carried out within urban space, involving both motorized and non-motorized modes, public or private, whose dynamics are directly related to urban planning, public policies, and available infrastructure (Vasconcellos, 2001).

The process of urbanization has intensified in recent decades: in 2018, about 55% of the world's population lived in urban areas, a percentage that may reach 68% by 2050 (UNITED NATIONS, 2019). This scenario increases the challenges associated with mobility, especially regarding the guarantee of accessibility and the sustainability of cities, in line with the guidelines of the 2030 Agenda.

In Brazil, the National Urban Mobility Policy (Federal Law No. 12,587/2012) established the requirement for Mobility Plans for municipalities with more than 20,000 inhabitants, prioritizing non-motorized and collective modes and reinforcing principles such as universal accessibility and sustainability. This regulatory framework highlights the need to ensure continued access to essential urban services in different contexts.

The concept of resilience, initially developed in the field of ecology (Holling, 1973), has been incorporated into urban studies as the capacity of systems to absorb impacts and maintain their essential functions (Timmerman, 1981; Folke *et al.*, 2010). In the context of mobility, resilience is related to maintaining access to destinations and essential services in the face of adverse events, such as energy crises or natural disasters (Santos, 2014; Chan and Schofer, 2016; De Castro Leiva *et al.*, 2020). Resilient systems depend on attributes such as modal diversity, connectivity, robustness, and adaptive capacity (Ribeiro and Gonçalves, 2019), reinforcing the importance of infrastructure for active modes and their role in daily access to services (Fernandes *et al.*, 2017; Oliveira *et al.*, 2015).

Given the complexity of urban mobility, the use of indicators becomes essential to analyze patterns, monitor guidelines, and support decision-making (Gudmundsson, 2004). These indicators must encompass social, economic, and environmental dimensions, providing an integrated view of the urban system (Maclaren, 1996). Considering the multiplicity of variables involved, the assessment of active mobility requires structured sets of indicators capable of synthesizing different dimensions of urban space.

Urban mobility is directly related to quality of life in cities, requiring the adoption of sustainable practices and the promotion of collective and non-motorized transport modes (RABELO, 2019). In this context, evaluating urban mobility demands the use of different methods and tools, with monitoring systems adapted to local specificities (PINTO *et al.*, 2024).

In this sense, the review of evaluation methods for urban infrastructure aimed at active modes shows that indicators can be organized into the following categories: access to essential destinations (a); configuration and connectivity of the urban road network (b); bicycle infrastructure (c); pedestrian infrastructure (d); intermodality elements (e); infrastructure for motorized modes (f); operational conditions of roadways (g); urban environmental aspects (h); road and personal safety factors (i); urban typology characteristics (j); comfort conditions for pedestrians and cyclists (k); elements related to user behavior (l); human physiology parameters (m); population characteristics (n); and institutional and governance dimensions (o).

The category of access to essential destinations (a) includes indicators of proximity and diversity of fundamental urban services, such as food, education, healthcare, financial services, and leisure, reflecting the ability of urban space to ensure accessibility through active modes and reduce motorized travel.

The configuration and connectivity of the urban road network (b) encompass indicators such as intersection density, block length, and street continuity, related to urban permeability, route choice, and the efficiency of walking and cycling trips.

Bicycle infrastructure (c) includes the presence and quality of bike lanes, signage, adequate width, pavement conditions, and parking facilities, expressing the physical support for cycling.

Pedestrian infrastructure (d) considers the conditions of sidewalks and circulation spaces, including their existence, width, surface quality, and absence of obstacles, being central to walkability assessment.

Intermodality elements (e) refer to the integration between active modes and public transport, such as stops and terminals, expanding the spatial reach of trips.

Infrastructure for motorized modes (f) includes facilities intended for automobiles, such as parking, which influence modal balance and transport mode choice.

Operational conditions of roadways (g) describe aspects such as speed and traffic flow, which impact safety, comfort, and risk perception among users of active modes.

Urban environmental aspects (h) involve elements such as tree cover and green areas, which contribute to environmental comfort and the attractiveness of active travel.

Factors related to road and personal safety (i) include lighting, signage, crossings, and accident occurrence, which are decisive for safety perception and the adoption of active modes.

Urban typology characteristics (j) include urban form and slope, conditioning the physical feasibility and continuity of trips.

Comfort conditions for pedestrians and cyclists (k) refer to urban furniture, shading, and microclimatic conditions that influence the travel experience.

Elements related to user behavior (l) concern habits, modal preferences, and individual attitudes, generally dependent on primary data collection.

Human physiology parameters (m) include aspects such as physical effort and health impacts, relevant for evaluating the adequacy of the urban environment, although with operational limitations at large scales.

Population characteristics (n) encompass socioeconomic and demographic variables, such as income, age, and population density, which influence demand and equity in urban access.

Finally, institutional and governance dimensions (o) refer to urban planning and land use policies, reflecting the role of institutional decisions in territorial organization.

Table 1 systematizes the evaluation methods identified in the literature, relating authors, categories of indicators, and application contexts, allowing the visualization of the diversity of approaches and the recurrence of categories according to the analyzed urban context.

Table 1- Comparative framework of active mobility assessment methods

Author(s)	Method	Indicator category															Application location
		a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	
Hoedl et al. (2010)	<i>Bikeability and Walkability Evaluation Table</i>	x		x	x			x	x	x						x	Graz – Austria
Cerin et al. (2011)	<i>Environment in Asia Scan Tool</i>	x			x					x	x	x					Hong Kong – China
Talavera et al. (2015)	<i>Pedestrian Level of Service</i>	x	x							x		x					Granada – Spain
Habibian e Hosseinzadeh (2018)	<i>Walkability Index (WI)</i>	x													x	x	Rasht – Iran
Lin e Wey (2018)	<i>Grey Analytic Network Process</i>	x	x	x						x							Taipei – Taiwan
Ruiz et al. (2018)	<i>Weighted Walkability Index</i>	x	x		x				x	x	x	x					Porto Alegre – Brazil
Taleai e Yameqani (2018)	<i>Healthy Walking Path Model</i>								x		x	x				x	Shiraz – Iran
Kim et al. (2019)	<i>Walkability Score</i>	x	x														Seoul – South Korea
Martins et al. (2019)	<i>Assessing resilience in urb. mob.</i>	x															São Carlos – Brazil; Maceió – Brazil
Rebecchi et al. (2019)	<i>Milan Walkability Measurement</i>	x	x	x	x				x			x				x	Milan – Italy
Alves et al. (2020)	<i>Walkability Index for Elderly Health</i>				x				x	x	x				x		Urban areas – Portugal
Arrelana et al. (2020)	<i>Bikeability Index</i>		x	x		x		x			x					x	Barranquilla – Colombia
Ignaccolo et al. (2020)	<i>Pedestrian Compatibility Index</i>		x		x	x				x	x						Acireale – Italy
Kamel et al. (2020)	<i>Bike Composite Index</i>	x		x												x	Vancouver – Canada
Orellana et al. (2020)	<i>Walk'n'Roll Mobile Assessment Tool</i>	x			x	x				x	x		x				Cuenca – Ecuador
Gossling e Mcrae (2022)	<i>Stated Preference - SP</i>		x	x	x												Berlin – Germany
Guzman et al. (2022)	<i>Walkability Index</i>	x			x			x	x	x		x					Bogotá – Colombia
Hardinghaus et al. (2021)	<i>Multifactorial Bikeability Index</i>		x	x				x	x								Berlin – Germany
Labdaqui et al. (2021)	<i>Street Walkability and Thermal Comfort Index</i>		x	x						x		x					Annaba – Algeria
Psarrou et al. (2022)	<i>Neighborhood Suitability Index</i>			x					x	x	x	x				x	Paris – France
Reggiani et al. (2022)	<i>Multi-layered Bikeability Assessment and BC</i>	x	x	x													Amsterdam – Netherlands
Schmid-Querg et al. (2021)	<i>Munich Bikeability Index</i>			x				x		x							Munich – Germany
Telega et al. (2021)	<i>New Approach for Measuring Walkability</i>	x			x	x											Krakow – Poland
Zhou et al. (2021)	<i>Sidewalk Walkability Index</i>	x			x	x			x		x						Salzburg – Austria
Karolemeas et al. (2022)	<i>Bikeability Index</i>	x	x					x	x		x						Zografou – Greece
Bartzokas et al. (2023)	<i>Microscale Walkability Index</i>				x	x				x		x					Mexico City – Mexico
Beecham et al. (2023)	<i>Connected Bikeability Index</i>		x	x				x	x	x							London – United Kingdom
Dai et al. (2023)	<i>Bikeability Index</i>	x				x							x				Xiamen – China
Jeong et al. (2023)	<i>Walkability Evaluation System</i>		x		x	x			x		x					x	Seoul – South Korea
Sánchez et al. (2024)	<i>15-Minute Walkability Composite Indicator</i>	x	x		x	x										x	Multiple cities – Europe
Tirolese et al. (2023)	<i>Walkability Index</i>	x	x						x	x						x	Milan – Italy

The categories most frequently observed in the literature are those related to the physical configuration of urban space and everyday access, especially access to destinations (a), urban road infrastructure (b), pedestrian infrastructure (d), and bicycle infrastructure (c). These categories concentrate indicators that can be directly measured through spatial data and public databases, such as intersection density, road network connectivity, block length, the existence and quality of sidewalks and bike lanes, as well as proximity to essential services such as commerce, education, leisure, food, and green areas. The recurrence of these categories reflects their methodological consolidation as central determinants of active mobility.

Categories associated with intermodal infrastructure (e) and road operational conditions (g) appear more sporadically in the analyzed methods, generally linked to studies that seek to integrate active modes with public transport or assess the influence of motorized traffic on safety and travel flow. Indicators such as stops, terminals, road speed, and traffic flow, although recognized as relevant, are not systematically incorporated into most indices, which limits more integrated analyses of the urban mobility system.

Safety (i) and comfort (k) show intermediate occurrence and high heterogeneity in the composition of their indicators. While some methods consider only basic elements such as public lighting, signage, and crossings, others incorporate more complex variables such as number of accidents, video surveillance, noise pollution, microclimatic conditions, urban furniture, and shading. This diversity highlights the lack of consensus regarding the appropriate level of detail and often reflects limitations related to data availability and standardization.

Categories related to urban environmental infrastructure (h) and urban typology (j) also appear frequently, particularly through indicators such as the presence of vegetation, street trees, urban form, and terrain slope. These elements are widely recognized as conditioning factors for comfort, physical effort, and the attractiveness of active travel, and are often used as structural or complementary variables in the analyzed methods.

In contrast, categories such as user behavior (l) and human physiology (m) are rarely explored systematically. Although conceptually relevant, indicators associated with these dimensions generally depend on primary data collection, individual monitoring, or biometric data, which restricts their application in urban-scale studies and compromises spatial replicability, especially in small and medium-sized cities.

Population characteristics (n) occupy an intermediate position in the literature, often used to contextualize results or as control variables. Indicators such as population density, income, age, gender, and motorization rate are widely recognized as conditioning factors of active mobility, but they rarely play a central role in index composition, appearing in an aggregated or complementary manner.

Finally, it is observed that the category of institutional and governance aspects (o), which includes indicators related to urban planning and land use, is only occasionally mentioned in the analyzed methods. Despite its relevance to the organization of urban space, its operationalization remains limited, particularly in studies that prioritize physical and directly measurable infrastructure metrics.

The analysis of existing approaches reveals advances in the assessment of active mobility, but also limitations regarding the integration between urban infrastructure and access to

essential services, as well as restrictions on replicability in small and medium-sized cities. These gaps point to the need for an instrument that incorporates well-established dimensions in the literature while remaining operationally feasible and applicable in different urban contexts.

In this scenario, the SIUMA index is introduced, designed to evaluate in an integrated manner the infrastructure for active modes and its relationship with everyday accessibility. The SIUMA index articulates urban configuration and access to essential services, supporting territorial diagnostics and the formulation of public policies from the perspective of resilience and the maintenance of urban functions through non-motorized travel.

The comparison with the studies presented in Table 1 shows that the selected indicators are aligned with the most recurrent categories in the literature, especially those related to road network connectivity, urban form and density, infrastructure for pedestrians and cyclists, and access to essential destinations. At the same time, the structure of the SIUMA index prioritizes indicators based on public data and suitable for geoprocessing, ensuring operational feasibility and replicability.

Categories such as user behavior and human physiology, although relevant, were excluded because they depend on primary data collection or data that are difficult to standardize. This methodological decision reinforces the practical, low-cost, and widely applicable nature of the SIUMA index.

Even with a more concise set of indicators, the SIUMA index encompasses essential functions of active mobility, addressing connectivity, road continuity, accessibility, safety, and comfort through variables such as physical barriers, coverage of essential services, low-speed streets, sidewalks, topography, and cycling infrastructure.

Unlike many methods developed for metropolitan contexts and dependent on specific datasets, the SIUMA index was designed for cities with up to 100,000 inhabitants, using exclusively public data, which expands its potential application in municipalities with lower technical and financial capacity.

The following section presents the methodological structure of the SIUMA index, detailing the selection criteria, the organization of indicators, and the calculation procedures.

## 2. METHODOLOGY

The index construction process began with a systematic review of international scientific literature related to the assessment of urban mobility focused on active modes of transport. Searches were conducted in the Web of Science and Scopus databases, as well as through the online academic article tracking platform Research Rabbit. Scientific articles published between 2010 and 2025 were included, adopting as a criterion the existence of at least ten citations per article. The keywords used in the searches were: *Urban mobility index*, *Urban mobility for active modes and index or assessment or method*, *Walkability and index or assessment or method*, and *Bikeability and index or assessment or method*. All 71 resulting articles had their abstracts individually analyzed in order to identify those whose themes were effectively aligned with the objectives of this research. At the end of this process, 33 studies were selected for presenting greater convergence with the analytical focus of the study.

The reading of these articles made it possible to identify the most recurrent indicators in studies on active mobility and urban accessibility, as well as to understand the city sizes for which these methods were predominantly developed. It also enabled the mapping of different data collection procedures employed, which included public and geospatial databases, interviews, questionnaires applied to the population, direct observation, and manual field data collection.

Regarding the categories of indicators to be addressed, those related to urban infrastructure were selected, which, according to Ahmed *et al.* (2024) and Castañon *et al.* (2025), are fundamental for mobility analysis. Additionally, indicators related to access to essential services were incorporated, since, according to Litman (2003) and Gudmundsson (2004), such elements are key to understanding the degree of resilience of cities in the face of crises. Finally, given the difficulty of obtaining data in cities with up to 100,000 inhabitants and the intention that the index be practically replicable by municipal managers and technicians, it was defined that the data collection process would be based on public databases made available by Geographic Information Systems (GIS) and municipal agencies. This premise aligns with the contributions of Ito and Biljecki (2021), who demonstrate that the integrated use of multiple databases significantly increases the accuracy, scalability, and territorial coverage of analyses, while reducing costs and overcoming limitations of manual data collection.

Regarding the construction of the index, the definition of domains, themes, and indicators was carried out based on the literature review, considering concepts of sustainable mobility, urban resilience, national and international index experiences, access to essential services, and data availability. This process resulted in an initial structure of the index. In order to assess the importance of the selected indicators, 19 experts in the field of urban mobility were consulted through an online form, representing national and international teaching and research institutions, as well as a specialized technical consultancy. Participating institutions included: São Paulo State University "Júlio de Mesquita Filho" (UNESP), Infraplan Consultoria, Federal University of Minas Gerais (UFMG), University of São Paulo (USP) – São Carlos Campus, Federal University of Itajubá (UNIFEI), University of Minho (Portugal), Federal University of Rio de Janeiro (UFRJ) – COPPE, University of Campinas (UNICAMP), Federal University of Ceará (UFC), Federal University of São Carlos (UFSCar), Federal University of Paraíba (UFPB), and State University of Santa Catarina (UDESC) (Souza and Manzato, 2024). The experts evaluated the relevance of each indicator, classifying them into three categories: (a) very relevant, when considered indispensable for composing the index; (b) relevant, when important but not essential; and (c) irrelevant, when its inclusion would not significantly change the composition of the index.

After incorporating the experts' suggestions regarding the inclusion and exclusion of indicators, the next step consisted of applying a new questionnaire, in which each expert was invited to rank the items according to their level of importance, following the methodology proposed by Souza and Manzato (2024), based on the Structured Pairwise Comparison (SPC) method, originally proposed by Sharifi *et al.* (2006). The SPC is a decision-support method that organizes the comparison between criteria in a structured manner, allowing the ranking of elements through simple pairwise comparisons and reducing inconsistencies associated with complex judgments. Its application in urban studies, especially in spatial modeling processes within Geographic Information Systems (GIS), was later expanded by Taleai *et al.* (2007).

In this procedure, each comparison between two items results in a position in the priority list: when the expert identifies a difference of weak importance, the item considered superior advances one position relative to the other. Thus, if item A is judged slightly more important than item B, A occupies position 1 and B position 2. When the difference is classified as strongly important, the superior item advances two positions, so that A remains in position 1 and B moves to position 3. This mechanism allows the qualitative perception of experts to be converted into a quantitative ranking structure, maintaining operational simplicity and clarity in the decision-making process.

After consolidating the rankings assigned by all experts, the positions of each item were summed, and the weights were then calculated using the inverse of the sum of positions, followed by normalization, ensuring that the total weights sum to 1.0. This procedure helps reduce the impact of contradictory judgments and provides greater robustness to the final hierarchy of indicators. As an example of this process, Table 2 presents the tabulation of judgments assigned to the indicators Urban road network connectivity (CR), Paved roads (VP), and Availability of public transport stops (DP), belonging to the Urban Transport theme, while Table 3 illustrates the normalization procedure for the indicators of this same theme, as proposed by Souza and Manzato (2024). The same tabulation, weighting, and normalization procedure was applied to all indicators, themes, and domains that compose the SIUMA index.

Table 2- Tabulation of the results of the degree of importance of the indicators of the Urban Transport theme

Indicator ranking	Respondent identification number																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
1°	CR	CR	CR	CR	CR	CR	CR	CR	CR	CR	VP	CR	CR	CR	DP	CR	CR	CR	CR	CR
2°	DP	VP	VP				DP	VP			DP		DP	CR	DP	DP				VP
3°			DP	DP	DP	DP			VP	DP	VP	DP	VP	VP	VP	VP	DP	DP	DP	DP
4°	VP	DP		VP	VP		VP	DP	DP			VP					VP	VP		
5°						VP				CR										

CR Urban road network connectivity  
VP Paved roads  
DP Availability of public transport stops  
Fonte: (Souza e Manzato, 2024).

Table 3- Normalization of the indicators of the Urban Transport theme

Indicators	Tabulation																	Sum	1/Sum	Normalization			
CR	1	1	1	1	1	1	1	1	1	5	1	1	1	2	1	1	1	1	1	1	24	0,042	0,537
VP	4	2	2	4	4	5	4	2	3	1	3	4	3	3	3	3	4	4	2	60	0,017	0,215	
DP	2	4	3	3	3	3	2	4	4	3	2	3	2	1	2	2	3	3	3	52	0,019	0,248	
																			0,078	1,000			

Fonte: (Souza e Manzato, 2024).

Once the methodological stage, which involved the conceptual definition of the SIUMA index, the identification and categorization of indicators, consultation with experts, and the definition of weighting and normalization procedures, is completed, the necessary framework is established for understanding its structure and operation. More specifically, its operationalization through the calculation procedures of the indicators, themes, and domains, as well as the final organization of the hierarchical structure adopted. This approach allows us to understand how the conceptual and methodological choices translate into a scoring system applied to the evaluation of urban infrastructure focused on active modes.

As a result of the process of defining the indicators, establishing the evaluation parameters, and assigning weights using the Structured Pairwise Comparison method, the calculation of the indicators, themes, and domains can be observed from the application of these previously defined parameters. The first item, shown here as an example, refers to the Urban Road Network Connectivity indicator (CR). Initially, the indicator parameters ( $cr1$ ,  $cr2$ ,  $cr3$ ,  $cr4$ ,  $cr5$ ) are scored according to the data collected. Next, the sum of these parameters is multiplied by the indicator's weight, resulting in its final score. Formula (1) exemplifies this calculation, and this model is adopted for all other indicators.

$$\text{Indicator score CR} = (\sum cr1 + cr2 + cr3 + cr4 + cr5) \times \text{Weight CR} \quad (1)$$

The calculation of the themes is carried out as follows: the sum of the indicators that make up the theme is calculated and multiplied by the weight of the theme, according to formula (2) exemplified below for the Urban Transport (TU) theme.

$$\text{Theme score (TU)} = (\sum CR + DP + VP) \times \text{Weight TU} \quad (2)$$

The calculation of the domains is performed as follows: the sum of the themes that make up the domain is calculated and multiplied by the domain weight. As per formula (3) exemplified below for the Urban Infrastructure (IU) domain, which is composed of the themes Urban Transport (TU) and City Topology (TC).

$$\text{Domain score (IU)} = (\sum TU + TC) \times \text{Weight IU} \quad (3)$$

The SIUMA index calculation is performed as follows: the domains that make up the index are summed, Urban Infrastructure (IU), Essential Services (SE), Active Modes of Transport (MA), according to the formula (4) exemplified.

$$\text{SIUMA Index} = \sum IU + SE + MA \quad (4)$$

Finally, the SIUMA index result represents the level of resilience of urban mobility in relation to the availability of infrastructure for active modes of transport for the evaluated sector/city. The proposed classification is presented in Table 4.

Table 4 - SIUMA Index Classification

SIUMA Index	Classification	Situation
Between 0.76 and 1.00	Satisfactory	The area features well-structured urban infrastructure in terms of availability of infrastructure geared towards active modes of transport, accessible essential services, and support for active modes of transport. In crisis scenarios, urban activities can continue to be developed without disruption.
Between 0.51 and 0.75	Good	The area has some vulnerabilities regarding the availability of infrastructure geared towards active modes of transport, however, it has a great capacity to adapt to adverse situations.
Between 0.26 and 0.50	Reasonable	The area has elements that contribute to resilience in urban mobility in terms of the availability of infrastructure geared towards active modes of transport, but in a limited way. In crisis scenarios, the response capacity of urban mobility is reduced.
Between 0.01 and 0.25	Poor	The area exhibits low resilience in urban mobility in terms of the availability of infrastructure geared towards active modes of transport. In adverse scenarios, the population is exposed to greater difficulties in getting around and a reduced capacity for adaptation.
Equal to 0.00	Unsatisfactory	The area lacks resilience in urban mobility in terms of the availability of infrastructure geared towards active modes of transport. There is a lack of urban infrastructure, access to essential services, and support for active modes. The population is vulnerable to crises, without viable alternatives for commuting using active modes of transport.

**3. RESULTS AND DISCUSSION**

The final version of the SIUMA index, hierarchically structured into domains, themes, and indicators, along with their respective evaluation parameters and established order of importance, can be seen in Table 5. This consolidated version comprises 14 indicators distributed across three main domains and their corresponding themes, forming the definitive structure of the instrument.

Table 5 - Final version of the SIUMA index

DOMAIN	THEME	INDICATOR
Urban infrastructure	Urban transport	<b>Urban road network connectivity</b> <i>Number of nodes present in the analysis area in relation to the ideal number of nodes</i>
		<b>Availability of public transport stops</b> <i>Number of public transport stops in the analysis area</i>
		<b>Paved roads</b> <i>Proportion of paved road length in relation to the total length of the existing road network in the analysis area</i>
	City topology	<b>Urban Form and Density</b> <i>Relationship between geometric form and population density in relation to the analysis area</i>
		<b>Physical Barriers</b> <i>Number of physical barriers existing in the analysis area<sup>2</sup></i>
		<b>Urban Topography</b> <i>Proportion of the area with accessible slope in relation to the analysis area</i>
Essential services	Access to essential services	<b>Low-Speed Roads</b> <i>Proportion of the length of the low-speed road network in relation to the total length of roads in the analysis area</i>
		<b>Access to education services</b> <i>Spatial coverage of education services considering an acceptable walking distance</i>
		<b>Access to food distributors</b> <i>Spatial coverage of food distribution services considering an acceptable walking distance</i>
		<b>Access to health services</b> <i>Spatial coverage of health services considering an acceptable walking distance</i>
Active modes of transport	Infrastructure for active modes	<b>Access to banks</b> <i>Spatial coverage of banking services considering an acceptable walking distance</i>
		<b>Roads with sidewalks for pedestrians</b> <i>Proportion of the length of roads with sidewalks in relation to the total length of roads in the analysis area</i>
		<b>Extent of bicycle infrastructure</b> <i>Proportion of dedicated bicycle lanes in relation to the total length of roads in the analysis area</i>
		<b>Bicycle parking</b> <i>Presence of bicycle racks or parking facilities in the analysis area</i>

Source: (Souza and Manzato, 2024).

Next, the results of the step aimed at obtaining the weights of the domains, themes, and indicators using the SPC method are presented in Table 6. This table shows the weights of each dimension (domain, theme, or indicator) and the weighted value of each indicator, considering the weights of the corresponding theme and domain.

Table 6 - Structure and weights of the SIUMA index

	Domain weight	Theme weight	Indicator weight	Weighted value
<b>URBAN INFRASTRUCTURE</b>	0.439			
<b>Urban Transportation</b>		0.522		
Connectivity of the urban road network			0.537	0.123
Availability of public transport stops			0.248	0.057
Paved roads			0.215	0.049
<b>City topology</b>		0.478		
Urban form and density			0.294	0.062
Physical barriers			0.288	0.060
Urban topography			0.233	0.049
Low-speed roads			0.184	0.039
<b>Essential Services</b>	0.299			
<b>Access to essential services</b>		1.000		
Access to education services			0.314	0.094
Access to food distributors			0.287	0.086
Access to health services			0.260	0.078
Access to banks			0.139	0.042
<b>ACTIVE MODES OF TRANSPORTATION</b>	0.262			
<b>Infrastructure for active modes of transport</b>		1.000		
Roads with sidewalks for pedestrians			0.502	0.132
Extension of infrastructure for bicycles			0.315	0.083
Bicycle parking			0.183	0.048

Source: (Souza and Manzato, 2024).

Tables 7 to 10 present the spreadsheets necessary for replicating the SIUMA index, organized in a way that clearly details, for each indicator, the parameters adopted, the scoring criteria, the weights assigned, and the formulas used in calculating the themes and domains. In this way, the spreadsheets allow for an understanding of how the input data is processed and constitute a practical tool for researchers, technicians, and public managers, enabling the application of the SIUMA index.

Table 7 - Spreadsheet for calculating indicators in the urban infrastructure domain.

Domains (Weight)	Themes (Weight)	Indicators (Weight)	Analysis Parameters	Score	Sector 1 Score Obtained	
Urban infrastructure (IU)	Urban transport (TU)	1° Connectivity of the urban road network (CR)	100% presence of real nodes in relation to ideal nodes	1.00	cr1	
			Between 75% and 99% presence of real nodes in relation to ideal nodes	0.75	cr2	
			Between 50% and 74% presence of real nodes in relation to ideal nodes	0.50	cr3	
			Between 25% and 49% presence of real nodes in relation to ideal nodes	0.25	cr4	
			Between 0% and 24% presence of real nodes in relation to ideal nodes	0.00	cr5	
			Weighted score for the indicator: Network connectivity			CR= (cr1+cr2+cr3+cr4+cr5) x Weight CR
		2° Availability of bus stops for public transport (DP)	100% of the sector area covered by the influence zone up to 500 meters from a bus stop	1.00	dp1	
			Between 75% and 99% of the sector area covered by the influence zone up to 500 meters from a bus stop	0.75	dp2	
			Between 50% and 74% of the sector area covered by the influence zone up to 500 meters from a bus stop	0.50	dp3	
			Between 25% and 49% of the sector area covered by the influence zone up to 500 meters from a bus stop	0.25	dp4	
	Between 0% and 24% of the sector area covered by the influence zone up to 500 meters from a bus stop		0.00	dp5		
	Weighted indicator score: Has stops for public transport.			DP= (dp1+dp2+dp3+dp4+dp5) x Weight DP		
	3° Paved roads (VP)	100% of roads paved	1.00	vp1		
		Between 75% and 99% of roads paved	0.75	vp2		
		Between 50% and 74% of roads paved	0.50	vp3		
		Between 25% and 49% of roads paved	0.25	vp4		
		Between 0 and 24% of roads paved	0.00	vp5		
		Weighted score for the indicator: Paved roads			VP= (vp1+vp2+vp3+vp4+vp5) x Weight VP	
	Weighted score for the topic: Urban Transport			TU= (CR + DP + VP) x Weight TU		

Table 8 - Spreadsheet for calculating indicators in the urban infrastructure domain.

Domains (Weight)	Themes (Weight)	Indicators (Weight)	Analysis Parameters	Score	Sector 1
					Score Obtained
Urban infrastructure (IU)	4° Urban Form and Density (FU)		High IC and high urban density	1.00	fu1
			High IC and medium urban density	0.75	fu2
			High IC and low urban density	0.50	fu3
			Medium IC and high urban density	0.75	fu4
			Medium IC and medium urban density	0.50	fu5
			Medium IC and low urban density	0.25	fu6
			Low IC and high urban density	0.50	fu7
			Low IC and medium urban density	0.25	fu8
			Low IC and low urban density	0.00	fu9
			Weighted score of the indicator: Urban form		
	5° Physical barriers (PB)		Absence of barriers	1.00	bf1
			Presence of barriers with overcoming structures	0.50	bf2
			Presence of barriers without overcoming structures	0.00	bf3
			Weighted indicator score: Physical barriers		
	6° Urban Topography (TU)		Slope equal to or less than 8.33%	1,00	tu1
			Slope greater than 8.33%	0,00	tu2
	Weighted score of the indicator: Urban topography			TU= (tu1+tu2) x Weight TU	
	7° Low-speed lanes		100% of low-speed roads		vb1
			Between 75% and 99% of low-speed roads		vb2
			Between 50% and 74% of low-speed roads		vb3
			Between 25% and 49% of low-speed roads		vb4
			Between 0 and 24% of low-speed roads		vb5
	Weighted score for the indicator: Low-speed roads			VB= (vb1+vb2+vb3+vb4+vb5) x Weight VB	
Weighted score for the theme: City topology			TC= (FU + BF + TU + VB) x Weight TC		
Weighted score for the domain: Urban infrastructure			IU= (TU + TC) * Weight IU		

Table 9 - Spreadsheet for calculating essential service indicators

Domains (Weight)	Themes (Weight)	Indicators (Weight)	Analysis Parameters	Score	Sector 1	
					Score Obtained	
Essential services (ES)	Access to essential services (ASE)	8° Access to education services (AE)	From 76% to 100% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	1.00	ae1	
			From 51% to 75% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0.50	ae2	
			From 26% to 50% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0.25	ae3	
			From 0% to 25% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0.00	ae4	
		Weighted score for the indicator: Access to education services			AE= (ae1+ae2+ae3+ae4) x Weight AE	
		9° Access to food distributors (AA)	From 76% to 100% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	1.00	aa1	
			From 51% to 75% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0.50	aa2	
			From 26% to 50% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0.25	aa3	
			From 0% to 25% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0.00	aa4	
		Weighted score for the indicator: Access to food distributors			AA= (aa1+aa2+aa3+aa4) x Weight AA	
		10° Access to health services (AS)	From 76% to 100% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	1.00	as1	
			From 51% to 75% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0.50	as2	
			From 26% to 50% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0.25	as3	
			From 0% to 25% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0.00	as4	
		Weighted score for the indicator: Access to health services			AS= (as1+as2+as3+as4) x Weight AS	
		11° Access to banks (AB)	From 76% to 100% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	1.00	ab1	
			From 51% to 75% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0.50	ab2	

	From 26% to 50% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0,25	ab3
	From 0% to 25% of the area of the sector covered by the zone of influence up to 1000 meters away from a unit	0,00	ab4
	Weighted score for the indicator: Access to banks	AB= (ab1+ab2+ab3+ab4) x Weight AB	
	Weighted score for the topic: Access to Services	ASE= (AE+AA+AS+AB) Weight ASE	
	Weighted score for the domain: Essential Services	SE= ASE x Weight SE	

Table 10 - Spreadsheet for calculating indicators of active modes of transport.

Domains (Weight)	Themes (Weight)	Indicators (Weight)	Analysis Parameters	Score	Sector 1	
					Score Obtained	
Active modes of transport (AM)	Infrastructure for active modes (IFA)	12° Streets with sidewalks for pedestrians (VC)	100% of streets with sidewalks	1.00	vc1	
			Between 75% and 99% of streets with sidewalks	0.75	vc2	
			Between 50% and 74% of streets with sidewalks	0.50	vc3	
			Between 25% and 49% of streets with sidewalks	0.25	vc4	
			Between 0 and 24% of streets with sidewalks	0.00	vc5	
			Weighted score for the indicator: Roads with sidewalks for pedestrians	VC= (vc1+vc2+vc3+vc4+vc5) x Weight VC		
		13° Extension of bicycle infrastructure (EI)	100% of roads with infrastructure	1.00	ei1	
			Between 75% and 99% of roads with infrastructure	0.75	ei2	
			Between 50% and 74% of roads with infrastructure	0.50	ei3	
			Between 25% and 49% of roads with infrastructure	0.25	ei4	
	Between 0 and 24% of roads with infrastructure		0.00	ei5		
		Weighted score for the indicator: Extension of bicycle infrastructure	EI= (ei1+ei2+ei3+ei4+ei5) x Weight EI			
	14° Bicycle Parking (EB)	Existence of bicycle racks or parking facilities by region within the study area.	1.00	eb1		
			0.00	eb2		
			Weighted score for the indicator: Bicycle parking	EB= (eb1+eb2) x Weight EB		
			Weighted score for the topic: Infrastructure for Active Modes of Transport	IFA= (VC+EI+EB) x Weight IFA		
	Overall score for Active Modes of Transport				MA= IFA x Weight MA	

#### 4. THE SIUMA INDEX AS A PLANNING TOOL

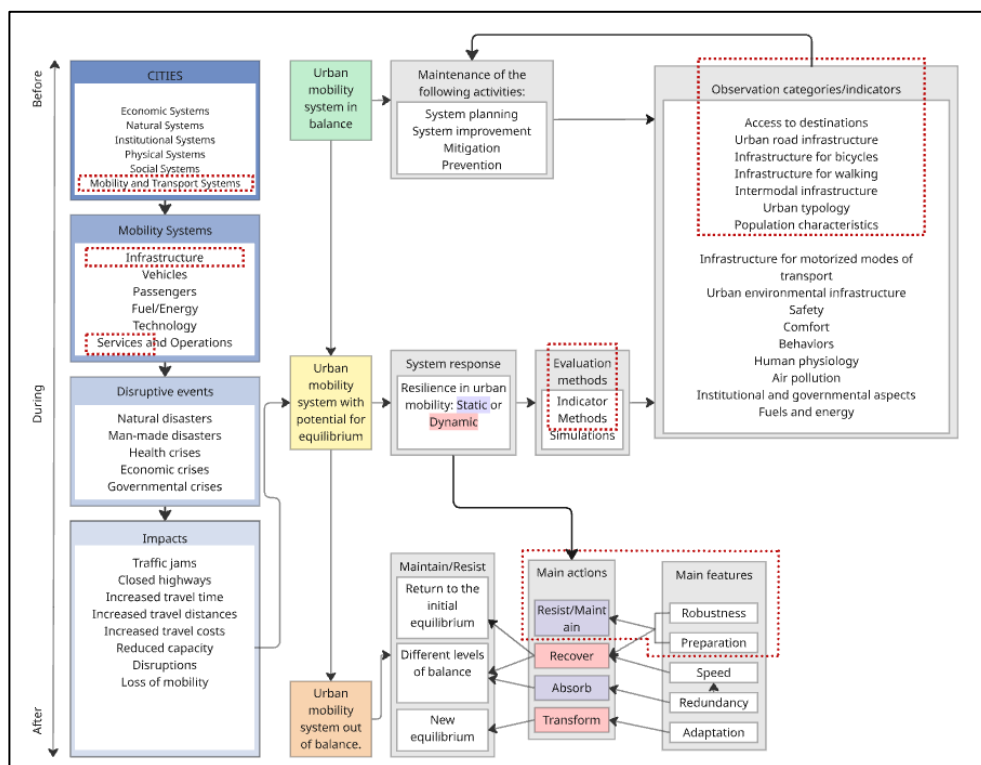
Beyond the methodological results, it is essential to discuss the role of the SIUMA index as a tool to support urban planning and the evaluation of infrastructure geared towards active modes. By integrating indicators related to urban configuration and access to essential services, the SIUMA index supports territorial diagnoses, guides the prioritization of investments, and contributes to the formulation of public policies. In this context, it also favors the incorporation of the resilience perspective in urban mobility, by highlighting structural conditions that influence the maintenance of access to urban functions in the face of disturbances.

To deepen this analysis, we adopt the urban mobility resilience framework proposed by Sassaron *et al.* (2025), derived from the urban resilience model of Ribeiro and Gonçalves (2019)

and adapted to the specificities of mobility systems. The model decomposes the system into components such as infrastructure, vehicles, passengers, services, technologies, travel behaviors, and service levels, in addition to distinguishing types of disruptive events — natural, anthropogenic, or operational — and their impacts, allowing the identification of vulnerabilities.

Sassaron *et al.* (2025) also incorporate the category “Assessment Methods” into the resilience cycle, encompassing indicators, analytical methods, and simulations in the equilibrium, impact, response, and recovery phases. In this sense, the SIUMA index reinforces the role of assessment methods as strategic instruments that articulate urban planning and resilience analysis. Figure 1 presents the aforementioned framework supplemented by the indicator categories identified in the literature review.

Figure 1- Resilience framework in urban mobility and indicator categories



Source: Adapted from Ribeiro and Gonçalves (2019) and Sassaron *et al.* (2025).

The SIUMA index is configured as a methodological diagnostic tool capable of contributing to different stages of the resilience process in urban mobility, based on the systematic analysis of its indicators. By including categories associated with the essential functions of active mobility, the index supports planning, mitigation, and prevention actions in contexts of system balance, allowing the identification of structural weaknesses in infrastructure and access to essential services, as well as prioritizing critical areas.

In situations of potential imbalance, the SIUMA index helps identify elements that can trigger instabilities, such as low road connectivity, discontinuities in pedestrian and cyclist routes,

physical barriers, and long distances to essential services. By highlighting these vulnerabilities, it offers technical support for corrective and preventive interventions.

When the system is already out of balance, the index helps assess the capacity to resist, maintain, and recover essential functions of urban mobility. By indicating sectors with better structural conditions — such as sidewalk continuity, alternative routes, proximity to services, and cycling infrastructure — the SIUMA index highlights where active modes of transport tend to remain operational in the face of adverse events, aligning with key attributes of resilience such as robustness, preparedness, and redundancy.

## 5. CONCLUSION

This article presented the conceptual and methodological construction of the Urban Infrastructure Services for Active Modes Index (SIUMA), developed with the objective of evaluating, in an integrated way, the availability of urban infrastructure intended for walking and cycling and its relationship with access to essential services. The proposal responds to the opportunity to develop instruments capable of diagnosing, based on public, standardized and replicable data, the structural conditions that influence active mobility and urban resilience, especially in small and medium-sized cities, with up to 100,000 inhabitants.

The results of the methodological stage show that the systematic literature review, associated with the categorization of indicators and consultation with experts, allowed the consolidation of a structure composed of 14 indicators organized into three fundamental domains. The application of the Structured Pairwise Comparison method for weighting the domains, themes and indicators provided consistency and coherence to the decision-making process, ensuring that the index synthesizes in a balanced way the different dimensions associated with urban infrastructure, essential services and active modes of transport. The final structure of the SIUMA index demonstrated potential for highlighting territorial patterns, identifying structural weaknesses, and revealing potential related to active mobility conditions and urban access.

In the process of constructing the index, it is important to pay attention to the limitations inherent in spatial analyses, especially the Modifiable Areal Unit Problem (MAUP), which is widely discussed in the literature. The adoption of smaller and standardized territorial units, such as the census tract, helps to mitigate this effect, increasing the sensitivity of the analysis to micro-variations in the urban environment. As evidenced by Valenzuela *et al.* (2022), this spatial unit allows capturing discontinuities in cycle paths, infrastructure breaks, variations in road connectivity, and differences in slope, in addition to integrating demographic, socioeconomic, and land use information, strengthening the accuracy of diagnoses produced in a Geographic Information System environment.

The SIUMA index is thus configured as a low-cost tool, easy to apply and with high replicability potential, especially in municipalities with technical and financial constraints. By relying exclusively on public data, the index contributes to the identification of territorial inequalities and offers technical support for urban planning and decision-making, supporting the prioritization of interventions aimed at improving active mobility and strengthening urban resilience.

As perspectives for future research, it is recommended that the SIUMA index be applied in different territorial contexts, in order to test its robustness and sensitivity to different urban configurations. It is also suggested that qualitative indicators associated with user perception be incorporated. Adapting the index for temporal analyses also represents a promising path, enabling the monitoring of structural transformations and the continuous evaluation of public policies.

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## DECLARAÇÕES

### CONTRIBUIÇÃO DE CADA AUTOR

Ao descrever a participação de cada autor no manuscrito, utilize os seguintes critérios:

- **Concepção e Design do Estudo:** Informe quem teve a ideia central do estudo e ajudou a definir os objetivos e a metodologia. Autores Renata Buzeti Garcia de Souza e Gustavo Garcia Manzato.
- **Curadoria de Dados:** Especifique quem organizou e verificou os dados para garantir sua qualidade. Autores Renata Buzeti Garcia de Souza e Gustavo Garcia Manzato.
- **Análise Formal:** Indique quem realizou as análises dos dados, aplicando métodos específicos. Autora Renata Buzeti Garcia de Souza
- **Aquisição de Financiamento:** Identifique quem conseguiu os recursos financeiros necessários para o estudo. Não foram necessários recursos financeiros para esse trabalho.
- **Investigação:** Mencione quem conduziu a coleta de dados ou experimentos práticos. Autora Renata Buzeti Garcia de Souza
- **Metodologia:** Aponte quem desenvolveu e ajustou as metodologias aplicadas no estudo. Autores Renata Buzeti Garcia de Souza e Gustavo Garcia Manzato.
- **Redação - Rascunho Inicial:** Indique quem escreveu a primeira versão do manuscrito. Autora Renata Buzeti Garcia de Souza
- **Redação - Revisão Crítica:** Informe quem revisou o texto, melhorando a clareza e a coerência. Autores Renata Buzeti Garcia de Souza e Gustavo Garcia Manzato.
- **Revisão e Edição Final:** Especifique quem revisou e ajustou o manuscrito para garantir que atende às normas da revista. Autores Renata Buzeti Garcia de Souza e Gustavo Garcia Manzato.
- **Supervisão:** Indique quem coordenou o trabalho e garantiu a qualidade geral do estudo. Autores Renata Buzeti Garcia de Souza e Gustavo Garcia Manzato.

### DECLARAÇÃO DE CONFLITOS DE INTERESSE

Nós, Renata Buzeti Garcia de Souza e Gustavo Garcia Manzato, declaramos que o manuscrito intitulado Avaliação da infraestrutura urbana e do acesso a serviços essenciais para mobilidade ativa: desenvolvimento do índice SIUMA não possui:

1. **Vínculos Financeiros:** Não possui vínculos financeiros que possam influenciar os resultados ou interpretação do trabalho.
2. **Relações Profissionais:** Não possui relações profissionais que possam impactar na análise, interpretação ou apresentação dos resultados.
3. **Conflitos Pessoais:** Não possui conflitos de interesse pessoais relacionados ao conteúdo do manuscrito.