Review Article

RBAFS Revista Brasileira de Atividade Física & Saúde
SOCIEDADE BRASILEIRA DE ATIVIDADE FÍSICA & SAÚDE

rbafs.org.br

Geospatial indicators of bikeability index as cycle-friendly city design: a systematic review

Indicadores geoespaciais do índice de bikeability como projeto de cidade amiga da bicicleta: uma revisão sistemática

AUTHOR'S

Alfredo Leopoldo Enrique Messenger Valenzuela[1]
Adalberto Aparecido dos Santos Lopes[1]
Pablo Antônio Bertasso de Araujo[1]
Marcelo Dutra Della Justina[1]
Gabriel Claudino Budal Arins[1]
Cassiano Ricardo Rech[1]

1 Universidade Federal de Santa Catarina, Departamento de Educação Física, Florianópolis, Santa Catarina, Brasil.

CORRESPONDING

Alfredo Leopoldo Enrique Messenger Valenzuela
alfredomessenger@gmail.com
Rua do Centro Esportivo - Carvoeira, Florianópolis, Santa Catarina, Brazil.
CEP: 88040-900.

DOI

10.12820/rbafs.27e0255

ABSTRACT

The aim was to identify the main geospatial indicators used in bikeability index through constructive methodological studies. The study protocol was registered in PROSPERO under the registration number CRD42020166795, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guide. Original studies indexed in the electronic databases Lilacs, PubMed, Science Direct, Scopus, SPORTDiscus, Trid, and Web of Science were selected. The review also included grey literature through Google Scholar, OpenGrey, ProQuest, and a list of references and documents pointed out by experts. After removing duplicates and analyzing titles and abstracts, the review considered only 11 out of the 703 initial papers, which provided 100 environment indicators with varied definitions and metrics for estimating the Bikeability index. The census tract was the most used unit of the analysis found in the papers, which used GIS (Geographic Information System) data besides self-reported information on environmental characteristics. The results indicate that the most usual indicators relate to infrastructure – existence and width of bike lanes – destination, slope, speed limit, and connectivity and intersections. The creation and maintenance of bicycle-friendly environments could consider the implementation of more infrastructure on flat and connected streets with changes in speed limits in neighborhoods, especially in regions with low density of intersections, to decrease accidents and increase cyclists' perception of safety.

Keywords: Environment design; Built environment; Bicycling; Geographic informations system.

RESUMO

Identificar os principais indicadores geoespaciais sobre a construção do índice de bikeability. O protocolo do estudo foi registrado no PROSPERO, sob o número de registro CRD42020166795, seguiu o guia (PRISMA). Foram selecionados estudos originais indexados nas bases de dados eletrônicas Lilacs, PubMed, Science Direct, Scopus, SPORTDiscus, Trid, Web of Science. A revisão também incluiu literatura cinza, além da lista de referências e documentos identificados por especialistas. A busca inicial identificou 703 artigos, após a retirada das duplicatas e análise de títulos, resumos e texto completo, 11 artigos foram incluídos na revisão. Um total de 100 indicadores geoespaciais do ambiente construído foram identificados com diferentes definições e métricas para estimar o índice de bikeability. O setor censitário foi a unidade de análise mais utilizada nos artigos, que utilizaram dados de SIG (Sistema de Informações Geográficas) além de informações autorreferidas sobre características ambientais. Os resultados indicam que os indicadores mais usuais dizem respeito à infraestrutura – existência e largura das ciclovias – destino, inclinação, limite de velocidade, conectividade e interseções. A criação e manutenção de ambientes amigos da bicicleta poderia contemplar a implantação de mais infraestrutura em vias planas e conectadas com mudanças nos limites de velocidade nos bairros, principalmente em regiões com baixa densidade de cruzamentos, para diminuir os acidentes e aumentar a percepção de segurança dos ciclistas.

Palavras-chave: *Planejamento ambiental; Ambiente construído; Ciclismo; Sistemas de informação geográfica.*

Introduction

Urban planning has often focused on cars because of the development characteristics of urban zoning with separate residential and commercial uses[1]. It has prevented and discouraged using active modes of transportation in large centers since it implies the need to travel long distances to access stores and services[2]. Such a scenario has brought adverse effects to the population, such as increased congestion, traffic insecurity due to high automobile speeds, and noise and air pollution due to CO_2[3] emissions.

Alternative means of transportation, such as bicycling, mitigate some effects in urban centers[4,5] and reduce health problems such as obesity, hypertension, and cardiovascular diseases associated with active travel[6-8]. From a public health perspective, a cost-benefit analysis of bike/pedestrian in Lincoln, USA, showed that for every dollar invested in it, there is a return on investment of $2.94 in health[9]. Studies point out the high potential that the use of bicycles can have in increasing levels of physical activity and reducing morbidities in the population, generating lower individual costs, since people use less the private and public health insurance[8,10]. There is also evidence of lower spending on daily commuting between home and services, favouring the economic growth of cities. Also, 85% of the London district representatives consider that using bicycles boosts business performance, allowing people to access the local business[11].

Bicycle-friendly cities such as Amsterdam[12], Copenhagen[13,] and Paris[14] have traditional and successful programs to encourage bicycling as a means of transportation. The reason is the favorable characteristics such as high street intersection density, mixed land use combinations, direct destination connections, and allocation of street space for pedestrians and cyclists, managing access modes through design to reduce traffic conflicts[15]. On the other side, in developing country cities such as Curitiba[16] and Cali[17], where bicycling prevalence is low, the lack of these features added to insecurity and poor or non-existent infrastructure can limit bicycling[17,18].

In this context, measures that concentrate environmental indicators in a grouped way, in the form of scores, can better represent the urban design structures related to the mobility of the population, specifically concerning bicycle use. Thus, bikeability proposes using indicators to represent areas with features related to bicycle use. The authors suggest using metrics and indicators to establish the bikeability index, which reveals dissensus and destandardization on the term and evaluation of the areas. Thus, this systematic review identifies and synthesizes the essential indicators used in the bikeability index construction.

Methods

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guide[19].

Protocol and Registration

The study protocol underwent registration in the International Prospective Register of Systematic Reviews (PROSPERO) under the registration number CRD42020166795, which is available at https://www.crd.york.ac.uk/prospero.

Eligibility Criteria

- **Inclusion Criteria**

The review evaluated the local variables and included observational and semi-experimental studies to build the bikeability index. It used quantitative and quantitative-qualitative analyses with subjective – questionnaires and target groups – and objective measures – Global Positioning System and Geographic Information System. The search was not restricted by language, date, or publication status, and includes articles that have been accepted but not yet published.

- **Exclusion Criteria**

The studies underwent the following exclusion criteria: 1) environment other than urban; 2) outcome variables not relating to the composition indicators of the bikeability index; 3) secondary studies (review articles, opinion articles, letters to the editor, books, book chapters, among others); 4) studies with qualitative results only; 5) studies that do not describe the indicators used in the composition of the bikeability index.

- **Information Source**

The conduction of individual search strategies guided each of the following electronic databases LILACS, PubMed, Science Direct, Scopus, SPORTDiscus, Trid, Web of Science. Also, there was the assistance of grey literature through Google Scholar, OpenGrey, and ProQuest. The additional articles result from hand-searching of references in the manuscripts from the review and contact through e-mail with experts who indicated relevant articles on the topic.

Research

The searches were adapted according to the electronic bases used. More information on search strategies is provided in Appendix 1, which can be found in the supplementary files for the online version of this article. All references were organized in EndNote software (EndNote X8® Basic Thomson Reuters, New York, USA) and duplicate articles were removed. The final date of the survey in all databases was December 7, 2019 and updated on July 12, 2020.

Selection of Studies

The selection of the studies took place in two phases.

In the first phase, two reviewers (ALEMV, PABA) independently evaluated the titles and abstracts found in the electronic databases discarding the papers that did not meet the inclusion criteria. Secondly, the reviewers (ALEMV, PABA) independently used the same selection criteria on the full text of the articles. The divergences in the first or second phase underwent discussion and agreement between the reviewers to find a solution. Not reaching a consensus, a third reviewer (AASL) was involved in the final decision. In both phases, the Rayyan QCRI[20] software assisted the selection of the studies.

Data Collection Process
Two reviewers (ALEMV, PABA) performed the data collection process independently. After individual collection, they carried out cross-checked information. The disagreements underwent discussion between the two reviewers, so they found a solution. A third reviewer (AASL) made the final decision when the others could not agree.

Data Extraction
The data extraction considered the registration of information – author, year of publication, city, country, definition of bikeability, unit of analysis, the number of units analyzed, and type of measurement – from the characteristics of the studies developing the bikeability index. We also extracted the categories and the respective indicators and synthesized them. The stages of identification, definition and grouping of classes for bikeability were conducted according to the indicators' relevance and frequency of the indicators, the grouping took place according to similar characteristics and as suggested by the literature[21-23] (Chart 1).

Analysis of the Risk of Bias in Individual Studies
As a methodological option, the risk of bias analysis was not performed due to the characteristics of the included studies, which were designed to develop models to estimate the bikeability index.

Results

Study selection
The initial search identified 703 articles that were found in the seven electronic databases searched. After removing duplicates, 470 articles were evaluated with an inter-rater agreement level of 95%. In addition, 197 studies have been identified in the grey literature, 5 being selected and included in study, 3 with 100% agreement between the evaluators. In the first selection phase (reading titles and abstracts), 31 studies were selected to be evaluated in full text with a level above 90% of agreement between the evaluators and others seven identified through references. Subsequently, 27 articles were excluded using the eligibility criteria (Appendix 2). The experts did not provide additional articles and in the update, there were no new articles to be included. Finally, 11 articles were included in the review process. Figure 1 shows a flowchart describing and detailing this process.

Characteristics of the Studies
The articles included were published between 2006 and 2019, of which 10 were published after 2012. The articles were found on only three continents, mostly in North America, with emphasis on the United States of America[24-27] (n = 4) and Canada[28] (n = 1). In South America, only Brazil[29] (n = 1) and Colombia[17] (n = 1) presented articles. While in Europe, Austria[30] (n = 1), Switzerland[31] (n = 1) and Norway[32] (n = 1) presented.

Among the articles in the review, only six[24,25,29,31-33] presented conceptual definitions for the term bikeability. The most commonly employed unit of analysis was the census tract[27-29,32] (n = 4), followed by neigh-

Chart 1 - Definition of indicators.

Indicator	Definition
Infrastructure	Support for the construction or maintenance of macro and micro scale characteristics of the urban environment. Related to physical facilities and / or policies that handle the use of certain locations.
Topography	Description of the physical structure of the land surface, identifying its contour, dimension, and position.
Land use	Delimitation and characterization of the use of the geographically demarcated areas. There can be integration between the different land uses and legislative control of the type of zoning.
Safety	It aims at the integrity of the citizen, through his / her perception and / or objective measure of the reliability of transit through a certain place. Its absence, caused by others and / or by poor conservation of urban furniture, may imply imminent or distant risk of damage.
Accessibility	A condition that ensures the citizen the possibility of enjoying, with autonomy and practicality, spaces, services, and urban facilities.

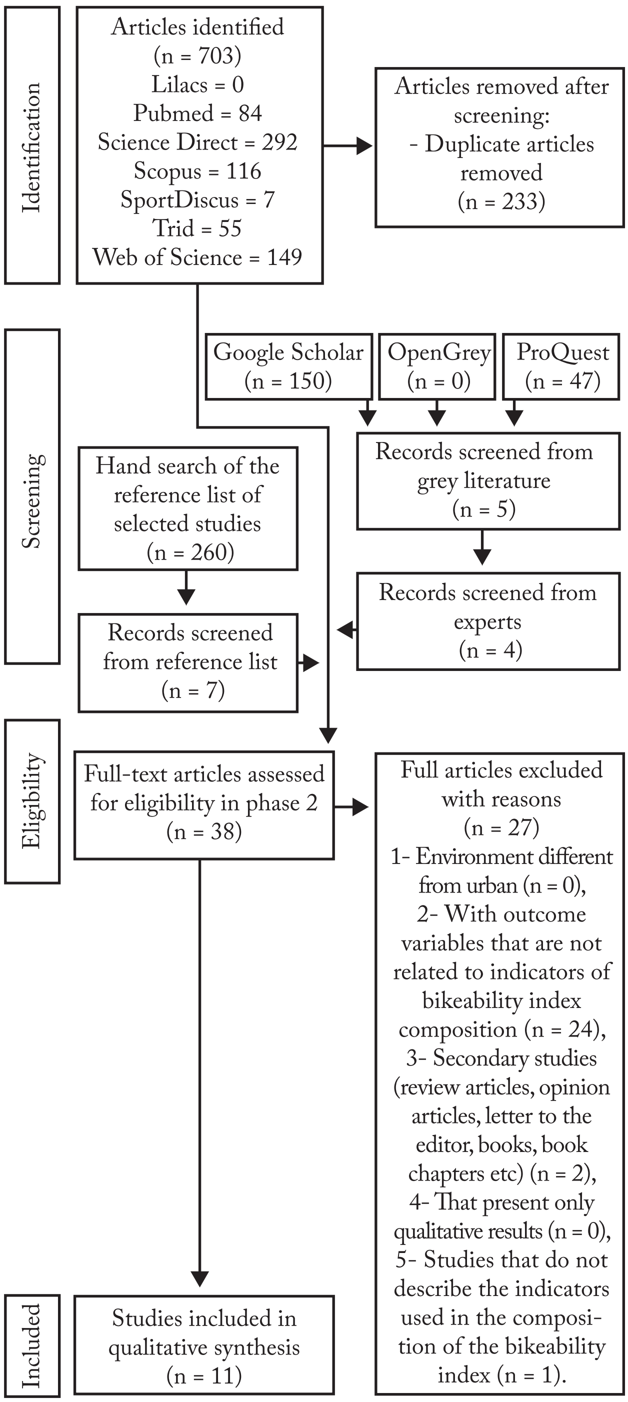

Figure 1 – Flow Diagram of Literature Search and Selection Criteria. Adapted from PRISMA.

borhood delineation[17,26,30] (n = 3). The number of the units shows up in six articles[24-26,28,32,33], ranging from 1 to 401. All 11 papers used Geographic Information System (GIS) data, and two of them[29,31] also employed self-reported information on environmental characteristics (Table 1).

Indicators for constructing the bikeability index

One hundred indicators were found, with varied definitions and metrics, distributed among the eleven articles, as shown in Table 2. According to the five pre-established categories (Table 1), infrastructure had 47 indicators, topography had 15, land use had 14, and safety and accessibility had 11. For the infrastructure category, the indicator bike lane width appeared in three articles[24,25,33]. For topography, slope appeared in four articles[27,29,32,33]. While for land use, destination appeared in four articles[25,26,28,31]. For safety, the speed limit appeared in three articles[24,25,32]. And finally, for the accessibility category, street connectivity/intersection appeared in four articles[27,28,32,33].

Out of the 11 papers, only the one from Asia[33] presented at least one indicator for each of the five categories, besides having used the most significant amount in the composition of the bikeability index, totaling 25. Summarizing the results, nine papers used at least one indicator from infrastructure[17,24,25,27-30,32,33] and diversified land use[24-31,33], seven used at least one from topography, and only six from safety and accessibility (Table 3).

Discussion

The review results show that the development of the bikeability index is still recent. Most of the publications have appeared since 2012. It sets the topic as contemporary and explains the small number of papers relating to the issue. There is a conceptual inconsistency of the term, possibly because of the differences in the results of structural modifications of cities, which encompass interdisciplinary features of an expanding area[34]. Among the six papers that defined bikeability, three presented the word convenience[25,31,32,] and two, the word comfort[25,32]. It is probably because such terms are frequently reported elements in research involving bicycling[25,30,32,35-37]. The preferred routes are those separated from motor vehicles, with lower traffic volume, well-established speed limits, and a larger connected and flat bicycle network[38]. Besides, the review results reveal specific indicators as essential when determining the index. Thus, based on the set of different existing concepts, in terms that make up the characteristics most favourable to bicycle use and in the indicators grouped into categories in this review, bikeability can be defined as: The ability to reach destinations in a comfortable, convenient, and safe way, by bicycle. Linking appropriate physical and political facilities in

Table 1 – Characteristics of bikeability index development studies included in the systematic review (n = 11).

Author	Year	City	Country	Definition of bikeability	Analysis Unit	Number of units analysed	Measurement scale	Measure type
Sisson et al[24]	2006	Mesa	USA	It is regarded as the ease in which street segments can be travelled on bicycle.	Street segment	175	Ordinal	GIS
Mc Neil[26]	2011	Portland	USA	N/D	Neighbourhood	26	Ratio	GIS
Lowry et al[25]	2012	Moscow	USA	An assessment of an entire bikeway network for perceived comfort and convenience and access to important destinations.	City community	1	Interval	GIS
Winter et al[28]	2013	Greater Vancouver	Canada	N/D	Census tract	401	Ratio	GIS
Mesa & Barajas[17]	2013	Santiago de Cali	Colombia	N/D	Neighbourhood	N/D	Interval	GIS
Krenn et al[30]	2015	Graz	Austria	N/D	Neighbourhood	N/D	Ratio	GIS
Greenstein[27]	2015	Austin	USA	N/D	Census tract	N/D	Ordinal Ratio	GIS
Motta[29]	2017	Curitiba	Brazil	It is used to determine the level of interaction between aspects associated with bicycling and the route environment, route distance and other factors that affect the conditions of a specific bicycle trip.	Census tract	N/D	Ordinal Interval	GIS +Self-reported
Lin &Wei[33]	2018	Taipei	Taiwan	Means general friendliness to bike riding within a zone, which can be a street block, neighbourhood, community or village.	Village	53	Interval	GIS
Grigore et al[31]	2019	Basel	Switzerland	A measure of ability and convenience to reach important destinations in the cycling network, based on perceived distances.	Quadrant 100x100	N/D	Ratio	GIS +Self-reported
Rugtvedt[32]	2019	Grenland	Norway	It evaluates a whole network of cycle paths regarding perceived comfort and convenience and access to a destination of interest.	Census districts School districts Urban areas	283 27 65	Interval	GIS

N/D = Does not describe; GIS = Geographic Information System.

Table 2 – Bikeability index indicators extracted from the studies included in the systematic review (n = 11).

Author (year)	Bikeability index categories				
	Infrastructure	Topography	Land use	Safety	Accessibility
Sisson et al. (2006)[24]	Outside lane width Bike lane width Pavement factors Number of through lanes Average daily traffic	-	Location factors	Speed limit	-
Mc Neil (2011)[26]		-	Destination type	-	-
Lowry et al. (2012)[25]	Width of outside lane Width of bike lane Width of shoulder % Occupied on-street parking Vehicle traffic volume % of heavy vehicles Pavement condition Presence of curb Number of through lanes	-	Importance of destination	Vehicle speed	Accessibility of location Time of travel Trip cost Distance

Continue…

Continue of **Table 2 –** Bikeability index indicators extracted from the studies included in the systematic review (n = 11).

Author (year)	Bikeability index categories				
	Infrastructure	Topography	Land use	Safety	Accessibility
Winter et al. (2013)[28]	Bicycle route density Bicycle route separation	Slope	Destination density	-	Connectivity of bicycle-friendly streets
Mesa & Barajas (2013)[17]	Bicycle facilities Extra bicycle amenities Parking hindrance	Elevation Slope Curvature Temperature of surface Vegetation index Normalized difference vegetation index Leaf water content index	-	Personal safety Safety aspects	-
Krenn et al. (2015)[30]	Cycling infrastructure Separated bicycle pathways Main roads without parallel bicycle lanes	Slope	Green and aquatic areas	-	-
Greenstein (2015)[27]	Bicycle facilities	Slope	Land use	-	Natural and physical barriers Network connectivity
Motta (2017)[29]	Bicycle lane Bicycle path Calm zone Bicycle route Shared sidewalk General roads Exclusive bus lanes	Slope	Mixed land use Residential density	Number of accidents with cyclists	-
Grigore et al. (2018)[31]	-	-	Center of destination (hectares) Number of workplaces	-	Perception of shorter distance
Lin & Wei (2018)[33]	Bikeway density Bikeway width Bikeway exclusiveness Bike parking space density Sidewalk width Sidewalk pavement Traffic volume Parking space for car/scooter Arcade density Shoulder width Bus route Night lighting	Average slope Tree Shade Air quality	Transit service Public bike service Public bike unavailability Mixed land use Green space	Law enforcement Smooth traffic Conflictless traffic	Intersection density Bikeway ratio
Rugtvedt (2019)[32]	Bicycle Infrastructure The share of heavy vehicles Road Category Road Surface Type Lane Width On-Street Parking Presence of Street Lights Daily Mean Traffic	Slope	-	Speed limit	Street connectivity

= There is no indicator for this category.

Table 3 – Synthesis of bikeability index indicators extracted from studies in countries of different incomes included in the systematic review (n = 11).

Author (year)	Country	Bikeability index categories				
		Infrastructure	Topography	Land use	Security	Accessibility
Sisson et al. (2006)24	USA†	Ö		Ö	Ö	
Mc Neil (2011)26	USA†			Ö		
Lowry et al. (2012)25	USA†	Ö		Ö	Ö	Ö
Winter et al. (2013)28	Canada†	Ö	Ö	Ö		Ö
Krenn et al. (2015)30	Austria†	Ö	Ö	Ö		
Greenstein (2015)27	USA†	Ö	Ö	Ö		Ö
Grigore et al. (2018)31	Switzerland†			Ö		Ö
Lin & Wei (2018)33	Taiwan†	Ö	Ö	Ö	Ö	Ö
Rugtvedt (2019)32	Norway†	Ö	Ö		Ö	Ö
Mesa & Barajas (2013)17	Colombia‡	Ö	Ö		Ö	
Motta (2017)29	Brazil‡	Ö	Ö	Ö	Ö	
Total		9	7	9	6	6

USA = United State of America; Ö = Category composed of at least one indicator; † = High-income countries according to World Bank classification; ‡ = Upper-middle-income countries according to World Bank classification.

cities, with favourable surfaces on the ground, integration with different land uses, aiming at the integrity of the citizens and the variability of choice options that ensure conditions of access to spaces and services[17,24-33].

The Geographic Information System (GIS) was the primary tool in every article identified in this review. In only two[29,31], the perception of the environment was along with GIS, which shows that it has been a relevant and emerging tool. However, GIS requires complementary measures to understand the physical characteristics of cities and quantitative and qualitative aspects of the environmental micro-scale, besides the perception of issues such as aesthetics and safety of the neighborhood that relates to the people's lifestyle[39]. Moreover, there is a lack of availability and enough detailing of georeferenced data to allow proper analysis of isolated indicators or grouped into scores[40]. These usually have secondary sources, large coverage areas, such as census sectors, being the unit of analysis[27-29,32] and, therefore, their acquisition does not aim the creation of bikeability indexes. Thus, it is necessary to filter the data from the existing databases and independently measure the environmental indicators through multiple tools. It is possible, for example, to identify the geographic location of bicycle paths[41], the actual routes traveled by bicycle[42], and the characteristics of the urban landscape related to bicycle use[43] as a mechanism to capture up-to-date indicators with accurate measurement and from various sources.

It is clear that, in the composition of the bikeability index, there is variability in the indicators, of which 100 concerning the built environment have different definitions and metrics, distributed among the eleven articles. The destandardization in the indicator use interferes with the comparison of studies. The lack of a standard in the use of these indicators can also be confirmed in a systematic review dealing with the effects of cycling interventions, which has also faced the diversification of scales, design of studies, of the data collection method and consequently in a diversity of indicators, in terms of definition and metric[44].

Topography was a category that appeared in the largest number of studies, with the slope of the terrain the most used indicator[27,29,32,33], respectively. The reason is the positive relationship between flat terrain[45] and bicycle use. Thus, flat terrain promotes the expansion of the bicycle network. Since there is no way to modify the terrain surface, the topography is relevant when building bicycle paths. Furthermore, when composing the bikeability index, it is possible to identify places with high slopes that can lead to the non-use of bicycle paths. Cyclists tend to avoid routes with steep gradients[46]. A gradient of up to 4% in slope degrees is satisfactory for bicycling[5]. However, the cultural context of each city should guide such aspects.

Concerning infrastructure, the bike lane width[24,25,33] was the most common indicator. The reason is that the authors relied on the Highway Capacity Manual (HCM), a manual that provides a methodology to calculate the level of service of the multimodal highway. It provides guidelines such as measures, limits, and procedures for automobiles, transportation modes, bicycles, and pedestrians[47-50]. However, a considerable number of indicators show the relevance of this category when composing the bikeability index, especially in the separation of bicycle and vehicle routes[28,30,33]. Evidence points to the importance of this separation and the feeling of safety while cycling[28,31,36,51,52], greater bicycle use[30,32,53-56,] and commuting by bicycle[57].

Regarding the safety category, the indicators speed limit and average daily traffic show up in more than two studies[24,32]. Research has shown how high traffic volumes and speeds affect the feeling of comfort when cycling. Bicycle users prefer routes where speed limits, average daily traffic, noise, air pollution, and interactions with motor vehicles are lower[58,59]. Thus, a local intervention can limit the speed of vehicular traffic in regions with a higher density of destinations and the presence of bicycles on the roads, providing a greater sense of security[58,59].

Among the land use indicators, the destination was the most frequent, corroborating three studies that found similar results. Close retail destinations were associated with a higher frequency of bicycling[25,26,60]. Furthermore, proximity to a variety of services, shops, and mass transit facilities has a positive effect on bicycle share programs[61-63].

Regarding accessibility, the key indicator was street connectivity, reinforcing the premise that regions with higher street connectivity are favorable for bicycle use as a mode of transportation[54,64,65]. In Switzerland[31], for example, this indicator composed the bikeability index, and the results showed that the higher the street intersection density, the shorter the distances perceived by cyclists[31]. On the other hand, more intersections could be more stressful or dangerous[67], requiring cyclists to pay more attention[68]. Cycling infrastructure assesssments include geometric dimensions, traffic characteristics and intersections[39,44,67.] In this sense, the master plans must also consider the relationship of the quality of the cycle paths that connect them to services and spaces, improving access to public transport stations by bicycle and modifying intersections with the presence of raised medians[69] and implementation of signs to protect cyclists from exposure to the dangers of the road traffic[45.66].

The variability in the composition of the bikeability index comes from the differences in the local geographic and social characteristics and the availability of data, which may be inexistent or restricted by the public administration[40]. In upper-middle-income countries, there are other social factors such as violence, which may have a higher weight in choosing whether to use the bicycle than in other more developed regions, making it necessary to take a specific approach in each context. Therefore, all these countries included 100% the safety category in the calculation of the bikeability index against 50% in high-income countries as shown in Table 3. Studies from South America countries have chosen to employ not only road safety, but also safety against crime, as indicators in the composition of their indexes[17,29]. In Curitiba, Brazil, a survey identified that the lack of safety was reported as a major barrier to bicycle use (22.4% of respondents), even above the absence of a bike path (14.1% of respondents)[18]. This calls for attention to interventions in these places with the aim of promoting the use of bicycles.

In this systematic review the studies show that the indicators related to the infrastructure category are the most widely used. Thus, one of the practical implications would be to invest in infrastructure for bicycle use, since it is a key element in promoting bicycle use in urban centres. Investing in cycling conditions could also be another important strategy to improve the conditions of bicycle use, such as reducing the speed limit of traffic on roads that have a cycle path. Although this does not necessarily change the infrastructure, it may result in safer cycling conditions. Another widely used element is access to destinations and street connectivity, including elements such as signage at intersections, generally associated with increased perceived user safety.

In addition to the indicators presented in this study for the ideal construction of a bikeability index, the main studies of this review will be presented by category. Although one study described indicators in all the categories[33], in order to enhance the index in representing the use of bicycles, it is important to complement the studies by category, for example, for infrastructure[32,33], topography[27,28,30], land use[26,31,33], security[17,29,32] and accessibility[25,31,32]. Data quality and arrangement, especially in upper- and middle-income countries, may vary across regions and over time. Indeed, data in developed countries are more available and typically of better quality[24-28,30-32].

Greenstein[27] reported that the presence of bicycle facilities, road network connectivity, topography and physical barriers are key indicators of bikeability, particularly types of land use. According to Grigore et al.[31], applying the index in Switzerland, provides information on which streets are suitable to includein the city's bicycle lane network, since it assesses the quality of streets and intersections. Lowry et al.[25], measured bikeability in Moscow, USA, using the bicycle suitability equation, demonstrating scenarios including new bike paths. In Portland, USA, Mc Neil[26], the methodology produced an objective bikeability score by destination of around[20] minutes away. In Cali, Colombia, Mesa & Barajas[17], the methodology addressed four categories for bikeability, highlighting environmental quality through satellite photos and safety. In Brazil, Motta[29] found no significant differences in the assessment of aspects that affect cycling and bicycle use, although assigning different weights to categories had an impact on the index. In Asia, Lin & Wei[33] considered interdependencies between criteria and zones using an analytical network process (ANP), analyzing the varied performance within a zone applying grey numbers in the criterion by measuring and evaluating bikeability across multiple criteria. In Norway, the method used by Rugtvedt[32] was based on a statistical summary with map layers of different sizes and different levels of aggregation. This approach is based on multi-scale indicators with weights and algorithms able to reproduce the results. In Mesa, USA, Sisson et al.[24] found that the streets around the schools were suitable for cycling and its prevalence was significantly higher in schools with limited transportation. In Vancouver, Canada, Winter et al.[28] reported that bikeability mapping provided a powerful visual aid and quantitative metric for identifying and prioritizing locations for new infrastructure. And in Austria, Krenn et al.[30]related that the cycling index was comprised of five components and GIS data. The tool detects areas where cycling conditions need to be improved.

New investigations can prioritize not only analyses with secondary geospatial data but also collect them for this purpose. Nevertheless, it seems that the adaptations made to indicators from secondary sources represent well the main characteristics of a bikeability index, especially when the necessary information is scarce. In addition, understanding the multi-indicators that can affect bicycle use in different regions of the world can be promoted by combined analysis about bicycles use policies. The integration and evaluations of activists, stakeholders, planners, and city managers, regarding the implementation and maintenance of infrastructures, en courage active commuting and the use of sci- entific evidence to design cycle-friendly cities.

As a main limitation, it was not possible to perform the risk of bias analysis due to the characteristics of the studies included in the review and the lack of a specific evaluation scale. Analysis of the risk of bias is a very important step in the systematic review and, whenever possible, should be performed. As strong points, the use of valid procedures for systematic search of evidence[19] stands out, and the inclusion of international and interdisciplinary bases that broadened the scope of the search. The search, reading and extraction method was also used by two independent reviewers, with high agreement in the stages (> 90%).

Finally, as a suggestion for future studies, public managers and health professionals can use the data from this review to identify which geospatial indicators are available in their municipalities and, thus being able to estimate the bikeability index or being able to collect data to estimate their own indicators. It is possible to propose adjustments to the indicators to better represent the local contextual characteristics. In addition, it is also possible to analyze the effects of the indicators on the use of bicycles, especially in low- and middle-income countries, such as Brazil. Association and intervention studies are needed that address outcomes related to physical activity and health, to improve the quality of information and its applicability, ensuring estimates of real impacts on the population from bikeability geospatial indicators.

In upper-middle-income countries, new evidence is needed on effective interventions that are contextually appropriate. The science of scalability will be greatly advanced by research that systematically identifies the key steps and processes required for successful scaling up of interventions. However, this requires more robust and standardized measures and indicators. Many of the databases are governmental or are on reports or websites rather than peer-reviewed scientific literature. This paucity of evidence in the peer-reviewed literature raises important questions about the methodological rigor and the internal and external validity of such evidence. Therefore, researchers from all regions of the world should do more program analysis studies to strengthen the global evidence base based on practice, which can be achieved using rigorous research methods to establish the impact of scaled-up interventions in the real world[71,72].

Conclusion

When building a bikeability index, one should consider the indicators of bike lane width, road gradient, destination, speed limits, and street intersection density in its composition. These indicators are interconnected and reflect characteristics that favor bicycling in urban centers. The main indicators found can be related to a data availability[71 72]. Also, the quality of these data can vary considerably between countries and even within a country or over the time. Countries with better development rates also tend to have better quality data. Planning and maintenance of bicycle-friendly environments could consider implementing more infrastructure in locations of flat and connected streets, changing the speed limits in neighborhoods, especially in regions with low-density street intersections, to decrease crashes and increase cyclists' perception of safety.

Conflict of interest

The authors declare no conflict of interest.

Funding

This work was carried out with the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - *Código de Financiamento 001*.

Author's contributions

Valenzuela, A.L.E.M. Conception of the first reviewer and study design, structuring of study selection criteria, search and selection, data extraction and analysis and manuscript preparation; Lopes, A. A. S. Third Reviewer / Specialist in geoprocessing study conception and design, structuring of study selection criteria, search and selection, data extraction and analysis, elaboration and critical review of the manuscript in all its stages; Araujo, P.A.B. Second Reviewer, conception and design of the study, structuring of the study selection criteria, search and selection, extraction and analysis of data and preparation of the manuscript; Justina, M.D.D. Involved in the initial conception of the study, writing and reviewing the manuscript; Arins, G.C.B. Conception of the research participant, study design, data analysis and preparation of the manuscript; Rech, C.R. Research Coordinator / Specialist Study conception and design, preparation and critical review of the manuscript in all its stages.

References

1. Mattioli G, Roberts C, Steinberger JK, Brown A. The political economy of car dependence: A systems of provision ap-proach. Energy Res Soc Sci. 2020;66:101486.
2. Chillón P, Molina-García J, Castillo I, Queralt A. What distance do university students walk and bike daily to class in Spain. J Transp Heal.2016;3(3):315–20.
3. Zhao X, Ke Y, Zuo J, Xiong W, Wu P. Evaluation of sustainable transport research in 2000–2019. J Clean Prod. 2020;256:120404.
4. Guzman LA, Arellana J, Alvarez V. Confronting congestion in urban areas: Developing Sustainable Mobility Plans for public and private organizations in Bogotá. Transp Res Part A Policy Pract. 2020;134 2019:321–35.
5. Eren E, Uz VE. A review on bike-sharing: The factors affecting bike-sharing demand. Sustain Cities Soc. 2020;54:101882.
6. Dinu M, Pagliai G, Macchi C, Sofi F. Active commuting and multiple health outcomes: a systematic review and meta-analysis. Sport Med. 2019;49(3):437–52.
7. Hamer M, Chida Y. Active commuting and cardiovascular risk: A meta-analytic review. Prev Med (Baltim). 2008;46(1):9–13.
8. Oja P, Titze S, Bauman A, de Geus B, Krenn P, Reger-Nash B, et al. Health benefits of cycling: A systematic review. Scand J Med Sci Sport. 2011;21(4):496–509.
9. Wang G, Macera CA, Scudder-Soucie B, Schmid T, Pratt M, Buchner D. A cost-benefit analysis of physical activity us-ing bike/pedestrian trails. Health Promot Pract. 2005;6(2):174–9.
10. McKim L. The economic geography of active commuting: Regional insights from Wellington, New Zealand. Reg Stud Reg Sci. 2014;1(1):88–95.
11. Aldred R, Sharkey R. Healthy Streets: a Business View. 2018;1–48.
12. Nello-Deakin S, Harms L. Assessing the relationship between neighbourhood characteristics and cycling: Findings from Amsterdam. Transp Res Procedia. 2019;41(2018):17–36.
13. Gössling S, Choi AS. Transport transitions in Copenhagen: Comparing the cost of cars and bicycles. Ecol Econ. 2015;113:106–13.
14. Koning M, Conway A. The good impacts of biking for goods: Lessons from Paris city. Case Stud Transp Policy. 2016;4(4):259–68.
15. Handy S. Making US cities pedestrian- and bicycle-friendly. Transportation, land use, and environmental planning. Elsevier Inc.; 2019. 169–87.
16. Reis RS, Hino AAF, Parra DC, Hallal PC, Brownson RC. Bicycling and walking for transportation in three Brazilian cit-ies. Am J Prev Med. 2013;44(2).
17. Mesa VG, Barajas DEP. Cali Bikeability Index Map: A tool for evaluating public investment and future needs. J Transp Geogr. 2013 4(1): 5–8.
18. Camargo EM. Barreiras e facilitadores para o uso de bicicleta em adultos na cidade de curitiba – um estudo com grupos [dissertação de mestrado]. Curitiba: Universidade Federal do Paraná; 2012.
19. Shamseer L, Moher D, Clarke M, Ghersi D, Liberati A, Petticrew M, et al. Preferred reporting items for systematic re-view and meta-analysis protocols (prisma-p) 2015: Elaboration and explanation. BMJ. 2015;349 2014:1–25.
20. Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A. Rayyan-a web and mobile app for systematic reviews. Syst Rev. 2016;5(1):1–10.
21. Duncan MJ, Winkler E, Sugiyama T, Cerin E, Toit L, Leslie E, et al. Relationships of land use mix with walking for transport: do land uses and geographical scale matter? J Urban Health. 2010;87(5):782–95.
22. Ferrer ALC, Thomé AMT, Scavarda AJ. Sustainable urban infrastructure: A review. Resour Conserv Recycl. 2018;128:360–72.
23. Saelens BE, Sallis JF, Frank LD. Environmental correlates of walking and cycling: findings from the transportation, urban design, and planning literatures. Annals of behavioral medicine. 2003;25(2):80-91.

24. Sisson SB, Lee SM, Burns EK, Tudor-Locke C. Suitability of commuting by bicycle to arizona elementary schools. Am J Heal Promot. 2006; 20(3):210-3.
25. Lowry M, Callister D, Gresham M, Moore B. Assessment of communitywide bikeability with bicycle level of service. Transp Res Rec. 2012 1;(2314):41–8.
26. McNeil N. Bikeability and the 20-min neighborhood: How infrastructure and destinations influence bicycle accessibility. Transp Res Rec. 2011 1;(2247):53–63.
27. Greenstein AS. Mapping bikeability: A Spatial analysis on current and potential bikeability in Austin , Texas. 2015.
28. Winters M, Brauer M, Setton EM, Teschke K. Mapping bikeability: A spatial tool to support sustainable travel. Environ Plan B Plan Des. 2013;40(5):865–83.
29. Motta BG. A bikeability index for Curitiba (Brazil). University of Twente; 2017.
30. Krenn PJ, Oja P, Titze S. Development of a bikeability index to assess the bicycle-friendliness of urban environments. Open J Civ Eng. 2015;05(04):451–9.
31. Grigore E, Garrick N, Fuhrer R, Axhausen IKW. Bikeability in Basel. Transp Res Rec. 2019;2673(6):607–17.
32. Rugtvedt JL. A dynamic scale approach for assessing bikeability with sensitivity for different user groups. Universität Salz-burg; 2019.
33. Lin JJ, Wei YH. Assessing area-wide bikeability: A grey analytic network process. Transp Res Part A Policy Pract. 2018 1;113:381–96.
34. Giles-Corti B, Vernez-Moudon A, Reis R, Turrell G, Dannenberg AL, Badland H, et al. City planning and population health: a global challenge. Lancet. 2016;388(10062):2912–24.
35. Winters M, Brauer M, Setton EM, Teschke K. Built environment influences on healthy transportation choices: Bicycling versus driving. J Urban Health. 2010;87(6):969–93.
36. Titze S, Stronegger WJ, Janschitz S, Oja P. Association of built-environment, social-environment and personal factors with bicycling as a mode of transportation among Austrian city dwellers. Prev Med (Baltim). 2008;47(3):252–9.
37. Moudon AV, Lee C. Walking and Bicycling: An evaluation of environmental audit instruments. Am J ofHealth Promot. 2003;18(1):21-37.
38. Winter M. Improving public health through active transportation: understanding the influence of the built environment on decisions to travel by bicycle. University of British Columbia; 2011.
39. Kellstedt DK, Spengler JO, Foster M, Lee C, Maddock JE. A scoping review of bikeability assessment methods. J Community Health. 2020;(0123456789).
40. Lopes AAS, Hino AAF, Moura EN, Reis RS. The Geographic Information System in environment, physical activity and health researches. Rev Bras Ativ Fís Saúde. 2019;23:1–11.
41. Silva ICM, Hino AA, Lopes A, Ekelund U, Brage S, Gonçalves H, et al. Built environment and physical activity: Do-main-and activity-specific associations among Brazilian adolescents. BMC Public Health. 2017;17(1):1–11.
42. Camargo EM, Alberico CO, Lopes AAS, Schipperijn J RR. Characteristics of the built environment on GPS- determined bicycle routes used by adolescents. Rev Bras Ativ Fís Saúde. 2020;24(e0106):1–7.
43. Cain KL, Geremia CM, Conway TL, Frank LD, Chapman JE, Fox EH, et al. Development and reliability of a streetscape observation instrument for international use: MAPS-global. Int J Behav Nutr Phys Act. 2018;15(1):1–11.
44. Mölenberg FJM, Panter J, Burdorf A, Van Lenthe FJ. A systematic review of the effect of infrastructural interventions to promote cycling: Strengthening causal inference from observational data. International Journal of Behavioral Nutrition and Physical Activity. BioMed Central Ltd.; 2019;16(1):1-31.
45. Weliwitiya H, Rose G, Johnson M. Bicycle train intermodality: Effects of demography, station characteristics and the built environment. J Transp Geogr. 2019;74 2018:395–404.
46. Fitch DT, Handy SL. Road environments and bicyclist route choice: The cases of Davis and San Francisco, CA. J Transp Geogr. 2020;85:102705.
47. Ryus P, Vandehey M, Elefteriadou L, Dowling RG, Ostrom BK. Highway Capacity Manual 2010.
48. American Association of State Highway and Transportation Officials. Guide for the Development of Bicycle Facilities, 4th Edition, 2012.
49. Transportation Research Board. Multimodal Level of Service Analysis for Urban Streets. 2008.
50. Harkey DL, Reinfurt DW, Sorton A. The Bicycle Compatibility Index: a level of service concept, implementation manual. 1998.
51. Hoedl S, Titze S, Oja P. The Bikeability and Walkability evaluation table: Reliability and application. Am J Prev Med. 2010;39(5):457–9.
52. Wahlgren L, Schantz P. Bikeability and methodological issues using the active commuting route environment scale (ACRES) in a metropolitan setting. BMC Med Res Methodol. 2011;11(1):1-20.
53. Winters M, Teschke K. Route preferences among adults in the near market for bicycling: Findings of the cycling in cities study. Am J Heal Promot. 2010;25(1):40–7.
54. Zhao P. The Impact of the Built Environment on Bicycle Commuting: Evidence from Beijing. Urban Stud. 2014;51(5):1019–37.
55. Cervero R, Duncan M. Walking, Bicycling, and Urban Landscapes: Evidence from the San Francisco Bay Area. Am J Public Health. 2003;93(9):1478–83.
56. Cervero R, Sarmiento OL, Jacoby E, Gomez LF, Neiman A. Influences of built environments on walking and cycling: Lessons from Bogotá. Int J Sustain Transp. 2009;3(4):203-26.
57. Braun LM, Rodriguez DA, Cole-Hunter T, Ambros A, Donaire-Gonzalez D, Jerrett M, et al. Short-term planning and policy interventions to promote cycling in urban centers: Findings from a commute mode choice analysis in Barcelona, Spain. Transp Res Part A Policy Pract. 2016;89:164–83.
58. Pikora T, Giles-Corti B, Bull F, Jamrozik K, Donovan R. Developing a framework for assessment of the environmental determinantsof walking and cycling. Soc Sci Med 56. 2003;56:1693–703.
59. Wahlgren L, Schantz P. Exploring bikeability in a metropolitan setting: Stimulating and hindering factors in commuting route environments. BMC Public Health. 2012;12(1):168.
60. Ma L, Dill J. Associations between the objective and perceived built environment and bicycling for transportation. J Transp Heal. 2015;2(2):248-55.
61. Wang K, Akar G, Chen YJ. Bike sharing differences among Millennials, Gen Xers, and Baby Boomers: Lessons learnt from New York City's bike share. Transp Res Part A Policy Pract. 2018;116:1–14.
62. Kabak M, Erbaş M, Çetinkaya C, Özceylan E. A GIS-based MCDM approach for the evaluation of bike-share stations. J Clean Prod. 2018;201:49–60.

63. Kaltenbrunner A, Meza R, Grivolla J, Codina J, Banchs R. Urban cycles and mobility patterns: Exploring and predicting trends in a bicycle-based public transport system. Pervasive Mob Comput. 2010;6(4):455–66.

64. Wang L. The Relationship between the Neighborhood Built Environment and Active Transportation among Adults: A systematic literature review. 2017;1(3):29.

65. Rybarczyk G. Examining the impact of urban morphology on bicycle mode choice. 2014;41:272–88.

66. Pucher J, Buehler R. Making Cycling Irresistible: Lessons from from The Netherlands, Denmark and Germany. 2008;28(4):495-528.

67. Teixeira IP, Rodrigues da Silva AN, Schwanen T, Manzato GG, Dörrzapf L, Zeile P, et al. Does cycling infrastructure reduce stress biomarkers in commuting cyclists? A comparison of five European cities. J Transp Geogr. 2020;88(August):102830.

68. Liu F, Figliozzi M, Caviedes A, Le H, Mai L. Utilizing Egocentric Video and Sensors to Conduct Naturalistic Bicycling Studies. Report NITC-RR-805. 2016;(August).

69. Strauss J, Miranda-Moreno LF, Morency P. Cyclist activity and injury risk analysis at signalized intersections: A Bayesian modelling approach. Accid Anal Prev. 2013;59:9–17.

70. Aldred R, Jungnickel K. Why culture matters for transport policy: The case of cycling in the UK. J Transp Geogr. 2014;34:78–87.

71. Reis RS, Salvo D, Ogilvie D, Lambert E V, Goenka S, Brownson RC. Scaling up physical activity interventions across the globe: stepping up to larger and smarter approaches to get people moving Physical Activity Series 2 Executive Committee. Lancet. 2016;388(10051):1337–48.

72. Butler EN, Ambs AM, Reedy J, Bowles HR. Identifying GIS measures of the physical activity built environment through a review of the literature. J Phys Act Health. 2011;8 Suppl 1(Suppl 1):91–7.

73. Panter J, Griffin S, Dalton AM, Ogilvie D. Patterns and predictors of changes in active commuting over 12 months. Prev Med (Baltim). 2013;57(6):776–84.

74. Ogilvie D, Bull F, Cooper A, Rutter H, Adams E, Brand C, et al. Evaluating the travel, physical activity and carbon im-pacts of a "natural experiment" in the provision of new walking and cycling infrastructure: Methods for the core module of the iConnect study. BMJ Open. 2012;2(1).

75. Krenn PJ, Oja P, Titze S. Route Choices of Transport Bicyclists: A Comparison of Actually Used and Shortest Routes. Int J Behav Nutr Phys Act. 2014 Mar;11(1):7p.

Received: 27/09/2021
Approved: 03/05/2022

Quote this article as:
Valenzuela ALEM, Lopes AAS, Araujo PAB, Della Justina MD, Arins GCB, Rech CR. Geospatial indicators of bikeability index as cycle-friendly city design: a systematic review. Rev Bras Ativ Fís Saúde. 2022;27:e0255. DOI: 10.12820/rbafs.27e0255