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Built environment bikeability as a predictor of cycling frequency: Lessons from Barcelona

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ABSTRACT

Background: Many cities are putting cycling at the centre of their sustainable transportation policies after the COVID pandemic. Cycling is seen as a desirable mode of transport in dense and compact areas and needs to be promoted accordingly. However, to date, only a handful of different bikeability indexes exist attempting to map biking conditions and the built environment's potential to promote biking as a modal choice on a city scale.
Methods: In this article, we use objective GIS data to map bikeability potential in the city of Barcelona. To do so we extracted the main bikeability components from an adhoc cycling survey and then create an index using ten spatial indicators. This bikeability index is mapped at a 100 $\times$ 100 m scale in the city of Barcelona. We then use actual travel behavior data extracted from a local representative travel survey to test the reliability of the index in predicting daily bike use.
Results: Results confirm the validity of the bikeability index as a predictor of the frequency of cycling. People living in areas with higher levels of built environment features associated with bikeability such as dedicated infrastructure, low accident rates and small slopes are more likely to use the bike more often.
Conclusions: Results validate our approach providing new methods to be used in further biking studies and a useful tool for policy and decision making. The use of our new bikeaiblity index is especially indicated for highly-dense, compact, Mediterranean-style cities.

1. Introduction

In recent years, there has been a shift in the mobility patterns of many cities around the world, as cycling is gaining popularity as an everyday mode of transport (Pucher and Buehler, 2017). Among the many factors partially explaining the preference for using a bike, environmental awareness, functional factors such as convenience or time management, the need to exercise, or affordability are frequently highly cited (Bhandal and Noonan, 2022; Charreire et al., 2021). This surge in the popularity of bikes has brought about a growing interest in the scientific community to create methods to assess the bike-friendliness of a particular built environment (Krenn et al., 2015a; Wysling and Purves, 2022). Among these methods, *bikeability indexes* are particularly popular, as they score the appropriateness of the built environment to support bicycling, considering both the factors that influence choosing the bicycle as the main mode of transport as well as the environmental factors that encourage traveling by bike. Building city-level bikeability indexes can help support decision-makers, monitor progress over time and facilitate communication with the general public (Kamel et al., 2020). This makes them a useful tool in the process of deciding interventions to improve cycling conditions as well as being a great way of displaying the distribution of areas in need of improvements to policymakers and the general population.

Since bikeability is a complex phenomenon, bikeability indexes can encounter issues when trying to incorporate the necessary number of built environment attributes. Previous literature has identified a significant number of built environment and contextual attributes that can be linked to cycling behaviour and they include bikeway density, bikeway width, bikeway exclusiveness, slopes or nearby green and blue areas, among others (Krenn et al., 2015b; Lin and Wei, 2018; Naess, 2012; Nielsen and Skov-Petersen, 2018; Pucher and Buehler, 2008; Winters et al., 2013). Additionally, biking has been found to be a means

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of transport that is susceptible to dynamic environmental factors, such as weather conditions or time of day (Hyland et al., 2018; Parkin et al., 2008; Wang et al., 2018; Winters et al., 2007). This makes measuring bikeability extremely challenging and geographically specific, as extrapolating the methods used in one city to another may not match reality, and factors affect each place differently.

In this article we aim to assess the spatial distribution of bikeability conditions in Barcelona by creating a bikeability index adapted to the urban morphology of Mediterranean and south European cities. Our index is built based on two data sources: (1) previous literature findings on the main determinants of biking, and (2) self-reported answers to an adhoc local survey on biking preferences and infrastructure needs. The validity of the index is later tested by modelling it as a predictor of bike use, employing the geolocated answers to an official travel survey. By modelling whether bikeability levels around the habitual residence are associated with biking habits, we also provide the growing research in the field with a framework that makes it easy for policy makers and experts to replicate other bikeability indexes in other local geographical contexts. To do so, section 2 of this article reviews the literature to date, section 3 shows the main variables and methods to create our bikeability index, section 4 presents the resultant mapping of the city and tests its power to predict likelihood of cycling, and sections 5 and 6 are left for the discussion and conclusion of the research, respectively.

2. Literature review

Over the last few years, biking has seen an upsurge in cities around the world as a healthy and environmentally-friendly alternative mode of transportation (Kellstedt et al., 2021; Krenn et al., 2015b; Pucher et al., 2010). Advances in technology in the past two decades have brought about innovative methodologies in many fields to assess communities and their support for bicycle (Kellstedt et al., 2021), a phenomenon known as “bikeability”. However, to this date, there is still no consensus over a universal definition of this term (Kellstedt et al., 2021; Muhs and Clifton, 2016). On the one hand, bikeability is defined as the “assessment of an entire bikeway network for perceived comfort and convenience and access to important destinations” (Lowry et al., 2012), and it is mainly employed as a tool for comparison between cities. On the other, bikeability can also be defined as the “extent to which the actual and perceived environment is conducive and safe for bicycling” (Kellstedt et al., 2021), a definition that focuses more on the suitability that a particular built environment offers for cycling.

The literature surrounding bikeability is still rather recent, and only a handful of different bikeability indexes still exist. These have been put to use in cities such as Vancouver (Kamel et al., 2020; Winters et al., 2013), Graz (Krenn et al., 2015b), Taipei (Lin and Wei, 2018) and Barranquilla (Arellana et al., 2020), among some others to assess the spatial distribution of bikeability on a city level. The limited number of bikeability index limits its reproducibility, as indexes respond to the morphological features of the urban areas where they have been tested/created (Winters et al., 2016). Given the sensitivity of biking behavior to local conditions and local biking culture however, a larger variation of indexes is clearly needed better representing cycling determinants in other urban areas with different built environment characteristics.

In general, bikeability has been found to align with walkability, but that is not always the case, as cycling has specific requirements on the personal level – equipment, experience – and on the infrastructure level – parking places, access to bike lanes –. In the case of biking, infrastructure usually plays a more important role than for walking (Kellstedt et al., 2021). Additionally, previous studies have found that biking determinants can also be motive-dependent and thus vary depending on the trip purpose (Beenackers et al., 2012).

Previous research has identified several additional factors that influence the decision to bike. Hilliness is considered a pivotal element in biking environments as hilly areas effectively dissuade from using active transport in general (Ma and Dill, 2017; Parkin et al., 2008; Winters et al., 2016). The availability of cycling infrastructure has been repeatedly found to be a key element in making an area more bikeable (Dill, 2009; Ma and Dill, 2017; Muhs and Clifton, 2016; Winters et al., 2010a; Winters and Teschke, 2010). Pucher et al. (2010) found that cyclists prefer having dedicated bike lanes to riding in mixed traffic, to which McNeil (2011) added that is especially true if they are segregated from other road users. Traffic calming measures around the trip origin, such as road markings or signage, are also associated with higher rates of cycling (Pucher and Buehler, 2008; Winters et al., 2010a). However, a single bike lane will not increase bikeability in an area per se, as it must be part of a wider, more complete and more varied network of bicycling infrastructure (Dill, 2009; Muhs and Clifton, 2016; Pucher et al., 2010). In this regard, Cervero et al. (2009) and Winters et al. (2010b) found that a high intersection density was associated with a greater likelihood of cycling in their studies of cycling behaviour in Bogotá and Vancouver. This effect is especially relevant in grid-pattern street networks (Dill, 2009; Marshall and Garrick, 2010). The association between cycling and intersection density, however, is still debated as Van Dyck et al. (2013) and Mitra and Nash (2019) found this relationship to be negligible across different cities in North America and Europe. Muhs and Clifton (2016) for their part, suggested that the reason behind that may be that having too many intersections also means more stops, effectively slowing travel speeds.

The role of parking spaces has also been considered in studies of bikeability (Lin and Wei, 2018; Van Dyck et al., 2013). To date, however, it is not clear whether an increase in parking facilities can encourage more bicycling, or if it is the lack of proper parking spaces what effectively dissuades from bike use (Pucher et al., 2010). In their study in Beijing, Shu et al. (2019) found that cycling was incentivized when the building entrance or exit was reasonably close to a bicycle parking rack.

Existing literature has also paid attention to the fact that cycling infrastructure does not only provide comfort to bike users but also safety, as they allow bike users not to have to share space with the automobile (Muhs and Clifton, 2016). While some studies have found that the relationship between perception of safety and cycling is unclear (Parkin et al., 2008; Van Dyck et al., 2013), others have found that perception of danger can hinder bicycle commuting significantly (Handy and Xing, 2011) or at least influence route choice (Winters et al., 2010b). These findings suggest that better perceptions of safety may foster increased biking. At the same time, having more bikes in the streets has been found to collectively increase security levels, improving the perception of safety and lowering the actual rate of bike accidents (Pucher et al., 2010). This trend, commonly labelled as “safety in numbers” (Elvik and Bjørnskau, 2017) is explained by the fact that increased number of bikes on the streets contribute to making them more visible to other modes of transport, an the same time that other road users learn how to safely interact with bikes. Perceptions of safety is a key component of bike modal choice and because of that a number of authors support safety to be included in bikeability indexes (Kamel et al., 2020).

Atmospheric wheather and climate are factors also commonly included in bikeability indexes, with rainfall and lower temperatures being associated with less willingness to cycle (Parkin et al., 2008; Winters et al., 2007). In addition, population density and land mix-use have been found to have a positive impact on cycling activity (Dill, 2009; Dill and Voros, 2007; Handy and Xing, 2011; Winters et al., 2010a), as they generate shorter trip distances, which are more readily covered by bicycle (Pucher et al., 2010).

However, conditions of the area – summarized in bikeability scores – cannot explain bike usage by themselves, as socio-demographic factors, attitudes and social environments have been found to determine the actual amount of bike use as well. In that context, women have been found to be less prone to cycling than men (Handy and Xing, 2011; Ma and Dill, 2017; Miralles-Guasch et al., 2022; Mitra and Nash, 2019; Parkin et al., 2008; Van Dyck et al., 2013; Winters et al., 2007). Older people are also more reluctant to cycling than their younger counterparts (Ma and Dill, 2017; Pucher and Buehler, 2008; Winters et al., 2007). Regarding social status, some studies consider that low-income people have a more negative perception of bikeability and lower cycling rates than wealthier individuals (Ma and Dill, 2017; Parkin et al., 2008), while others have found that cycling rates are negatively associated with income (Van Dyck et al., 2013; Winters et al., 2007). Similarly, it is also important to take into account the attitudes of commuters themselves, particularly their comfort level with bicycling and how much they enjoy biking as an activity in itself (Handy and Xing, 2011). Additionally, we must bear in mind that trip distance is a fundamental consideration in mode choice (Winters et al., 2010a), especially commuting cyclists, who are more sensitive to distance and less sensitive to most other variables compared to other cyclists (Broach et al., 2012), which indicates that not all variables in a bikeability index have the same importance for every individual.

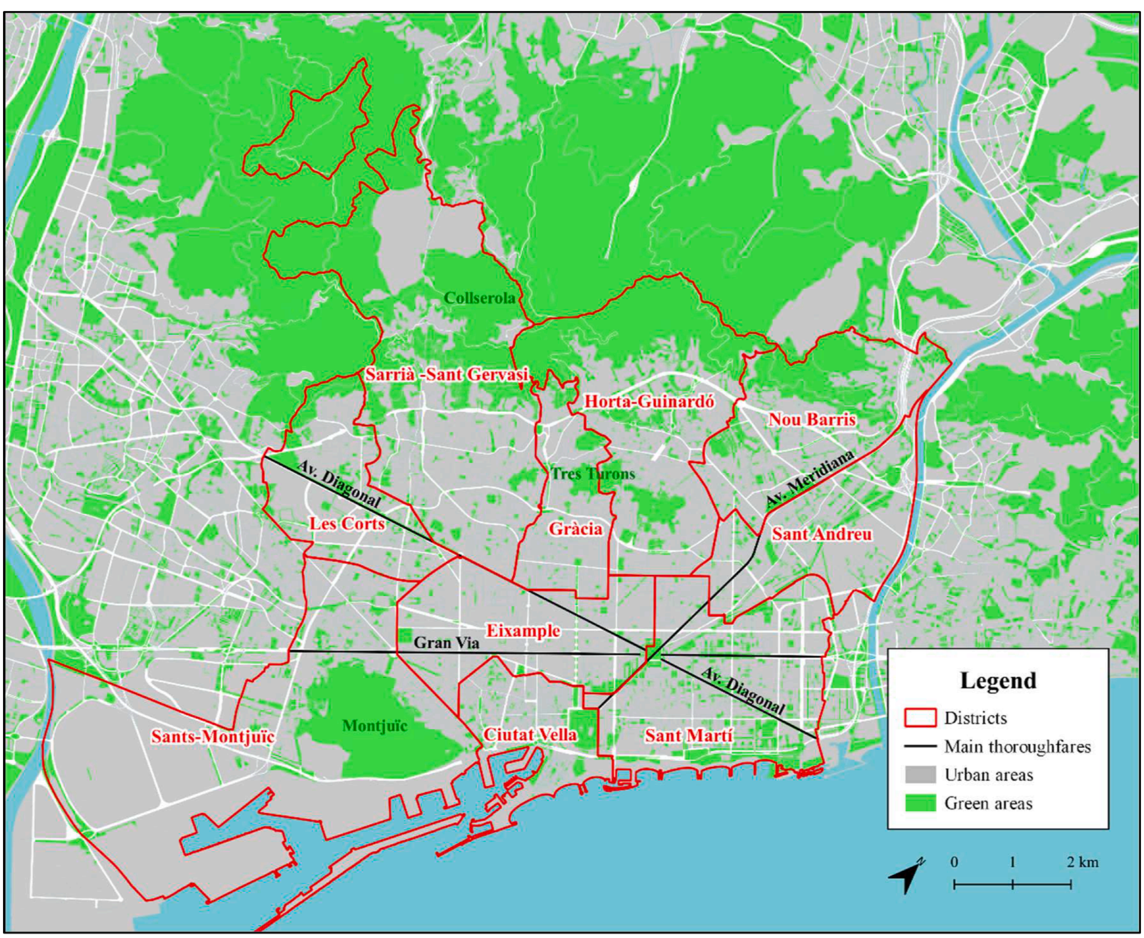
3. Methods

3.1. Study area: Barcelona

Barcelona lies on the western Mediterranean coast in north-eastern Spain. It gathers a population of around 1.6 million inhabitants in an area of circa 100 km^2, making it one of the densest cities in Europe, with an intense land-use mix in relatively short distances (Delclòs-Alió and Miralles-Guasch, 2018; Marquet and Miralles-Guasch, 2015). These are key elements in making a city attractive for biking (Dill, 2009; Dill and Voros, 2007; Handy and Xing, 2011; Winters et al., 2010a), as they generate shorter trip distances, which are more readily covered by bicycle (Pucher et al., 2010). Furthermore, the city has a Mediterranean climate, which is warm and dry most days, conditions that favour cycling (Parkin et al., 2008; Winters et al., 2007). Additionally, the grid pattern, which is exemplified in Barcelona with the Eixample district, provides consistently high levels of connectivity (Dill, 2009) (Fig. 1).

3.2. Variables and data sources

In order to select the main variables that play a role in cycling in Barcelona from a user perspective and later assess their relative importance in the overall bikeability of the city, we used responses to a local bike-user survey)Enquesta Baròmetre de la Bicicleta) (Generalitat de Catalunya, 2019). The survey is carried out annually since 2006 at the request of the Generalitat de Catalunya, and comprises a sample of 800 people, interviewed via telephone, as well as an oversample of 200 cyclists, surveyed online. Within the survey, bike users (n = 290) were asked to state the main difficulties and perceived barriers when using a bicycle as a daily mode of transport (Generalitat de Catalunya, 2019). We used the answers to the survey to identify the basic variables that needed to be included in the index (Table 1). We then crossed the obtained variables with the most commonly utilized variables in previous bikeability indexes available in the literature. Both the answers to the survey and the findings from the literature review were used to assign weights to each variable within the final bikeability index. That method allowed us to attain to the perceived needs of local bike users while also incorporating previous findings from the most common international bikeability indexes.



Source: Own elaboration.

Fig. 1. Study area map: Barcelona.

Table 1
Results of the answer to the question "*In a city, which is the main difficulty when moving around cycling?*" in the Enquesta Baròmetre de la Bicicleta (2019), variable and associated weight assigned.

Original variable	% of respondents	Variable (abbreviation)	Weight
Interaction with motor transit	22,1%	Traffic (T_i)	40 %
Insufficient adequate spaces	15,9%	Infrastructure (I_i)	15 %
		Connectivity (C_i)	15 %
Theft risk	15,6%	–	–
Orography conditions	11,2%	Topography (S_i)	20 %
Lack of habit	9,4%	–	
Atmospheric conditions	8,7%	–	
Insufficient parking facilities	6,6%	Parking spaces (P_i)	10 %
Lack of accessibility in public transit	4,2%	–	
Others	0 %	–	
Not answered	0,4%	–	

Source: Enquesta baròmetre de la bicicleta 2019 (Generalitat de Catalunya, 2019).

Variables identified as a significant barrier to bike use such as theft risk, atmospheric conditions, lack of habit and difficulties regarding their carriage on public transit could not be included due to lack of objective and geolocated associated data. The variable "insufficient adequate spaces" was divided into two equally-weighted variables, as some studies consider availability of cyclable infrastructure and its connectivity to have a different impact on bikeability (Lin and Wei, 2018; Winters et al., 2013).

Table 2 summarizes the included final bikeability index and their correspondent indicators. All the data has been collected from the Barcelona Open Data website (Ajuntament de Barcelona, 2021d), except for the topography variable, which has been calculated using the digital elevation model available from the Institut Cartogràfic i Geològic de Catalunya (Institut Cartogràfic i Geològic de Catalunya, 2021). All variables were calculated using a grid map with cells (i) of 100 m × 100 m that covers all the municipality of Barcelona.

The ***Traffic*** (T_i) indicator aims to represent the level of interaction of bikes with motor vehicles. It is computed as the ratio of bike collisions per bicycle trips in any given cell. Using the gauging data from different stations, we estimated the gauging for all the city using the interpolation tool in ArcMap. The value of each cell is the standardized z value of the coefficient of the total bike collisions in a 5-year period (as reported by Guàrdia Urbana – Barcelona's police department) occurred within a 150 m around the centroid of each cell divided by the estimated gauge of bicycle traffic in the same area. This buffer size is commonly used in the literature when assessing biking collisions (Urban Systems, 2015). As fewer accidents mean better bikeability, the resulting z values have been turned into negative values.

The quality of the ***Infrastructure*** (I_i) has been estimated by calculating the distance from the centroid of each cell to the nearest biking infrastructure using the *Near* tool in ArcMap. Distance to segregated cycle paths was assigned three times more weight than distance to painted cycle lanes (also known as "sharrows"), as suggested by the literature (Walk Score, 2021). Additionally, all distances further than 400 m have been re-coded to 400.1 m to avoid a cell close to one type of infrastructure but far from another getting a misleading score. As in this case lower values represent better bikeability levels, z values have been turned into negative values.

Connectivity (C_i) is referred as the density of intersections. We have counted the number of cycling infrastructure intersections inside a 400 m buffer from the centroid of each cell following the method by Winters et al. (2013). The weight has also been modified depending on the nature of the infrastructure (Urban Systems, 2015), with intersections of segregated cycle paths being assigned the largest weight, followed by intersections between segregated cycle paths and sharrows and finally intersection between sharrows being assigned the smallest weight. Results have been transformed into z values.

The estimate count of ***Parking spaces*** (P_i) within each cell has been calculated by counting the number of bike racks and *Bicing* stations (Barcelona's public bicycle-sharing system) within a 240 m buffer from the centroid of each cell. These 240 m are estimated to be the maximum distance a person would walk to access a bike (Shu et al., 2019). Results are expressed also as z values.

Topography (S_i) has been estimated based on a digital elevation model. Using the Slope tool in ArcGis, we have created a slope map of Barcelona and, later, with the Zonal Statistics tool, we have measured the mean percent rise in a 120 m-radius buffer from each cell centroid, a distance used by the Manual for the Design of Cyclepaths in Catalonia (Medina and Hernández, 2008) and also roughly the size of a block in Eixample district. A rise higher than 25 % has been recoded as being 25.01 % in order to limit the range of subsequent z values, which have been later turned into negative.

Thus, to calculate the Bikeability value for each cell we have used the following formula:

$$B_i = (0.4 \times T_i) + (0.15 \times I_i) + (0.15 \times C_i) + (0.1 \times P_i) + (0.2 \times S_i)$$

The resulting bikeability index ranges from 0 to 1, 1 expressing the most bikeable areas and 0 the least bikeable ones.

3.3. Validating the index

To validate the index, we used mobility data from the EMEF18 and EMEF19 travel surveys. These are annual CATI (Computer Assisted Telephone Interviews) surveys carried out by the Autoritat del Transport Metropolità and comprise a sample of 10,100 individuals. These surveys have been repeatedly used not only by transportation management in the Barcelona area but also by academic literature (Cubells et al., 2020; Maciejewska et al., 2019; Marquet et al., 2017; Marquet and Miralles-Guasch, 2018). Their main objective is to assess the habits and attitudes of the population in the Barcelona metropolitan region regarding their mobility and commuting patterns during working days. We assigned bikeability values to EMEF18 and EMEF19 participants based on the average bikeability values found in a 500 m buffer around their

Table 2
Diagram of the variables and indicators used.

Variable Indicator	Definition (measured in a zone to be assessed)
Traffic (T_i)	
Collisions involving bicycles[1]	Number of total bike collisions in a 5-year-period within a 150 m radius
Cyclist volume[2]	Number of daily bicycles within a 150 m radius
Infrastructure (I_i)	
Nearest cycle path[3]	Proximity to cycleway with exclusiveness (in m)
Nearest cyclable lane[3]	Proximity to cycleway without exclusiveness (in m)
Connectivity (C_i)	
Intersections of cycle paths[3]	Number of intersections between cycle paths within a 400 m radius
Intersections of cyclable lanes[3]	Number of intersections between cyclable lanes within a 400 m radius
Intersections of cyclable paths and cyclable lanes[3]	Number of intersections between cycle paths and cyclable lanes within a 400 m radius
Parking spaces (P_i)	
Distance to *Bicing* stations[4]	Proximity to bicycle-sharing system stations (in m)
Distance to bike racks[5]	Proximity to open-air public bike racks (in m)
Topography (S_i)	
Percent rise[6]	Mean percent rise within a 120m radius

[1] (Ajuntament de Barcelona, 2019b).
[2] (Ajuntament de Barcelona, 2019a).
[3] (Ajuntament de Barcelona, 2021a, 2021b, 2021e).
[4] (Ajuntament de Barcelona, 2021c).
[5] (Ajuntament de Barcelona, 2015).
[6] (Institut Cartogràfic i Geològic de Catalunya, 2021).

home address. We then tested the association between bikeability levels and the odds of choosing bike as a modal choice. First, we used an ANOVA to test the associations between living in a high-bikeable environment and cycling as the main mode of transportation. Then we run a binary logistic regression model to test the association between bikeability and choosing a bike as a modal choice after adjusting for key socioeconomic variables such as gender, age, education level and job status.

4. Results

The process of creating and testing the bikeability index is structured in two parts. First, we have mapped the distribution of the index values in the city of Barcelona, as well as the distribution of the five main environmental features that compose the index based on the 100 × 100 m grid. On a second stage, we have tested the validity of our index comparing it with the results obtained from the local official travel survey (EMEF2019).

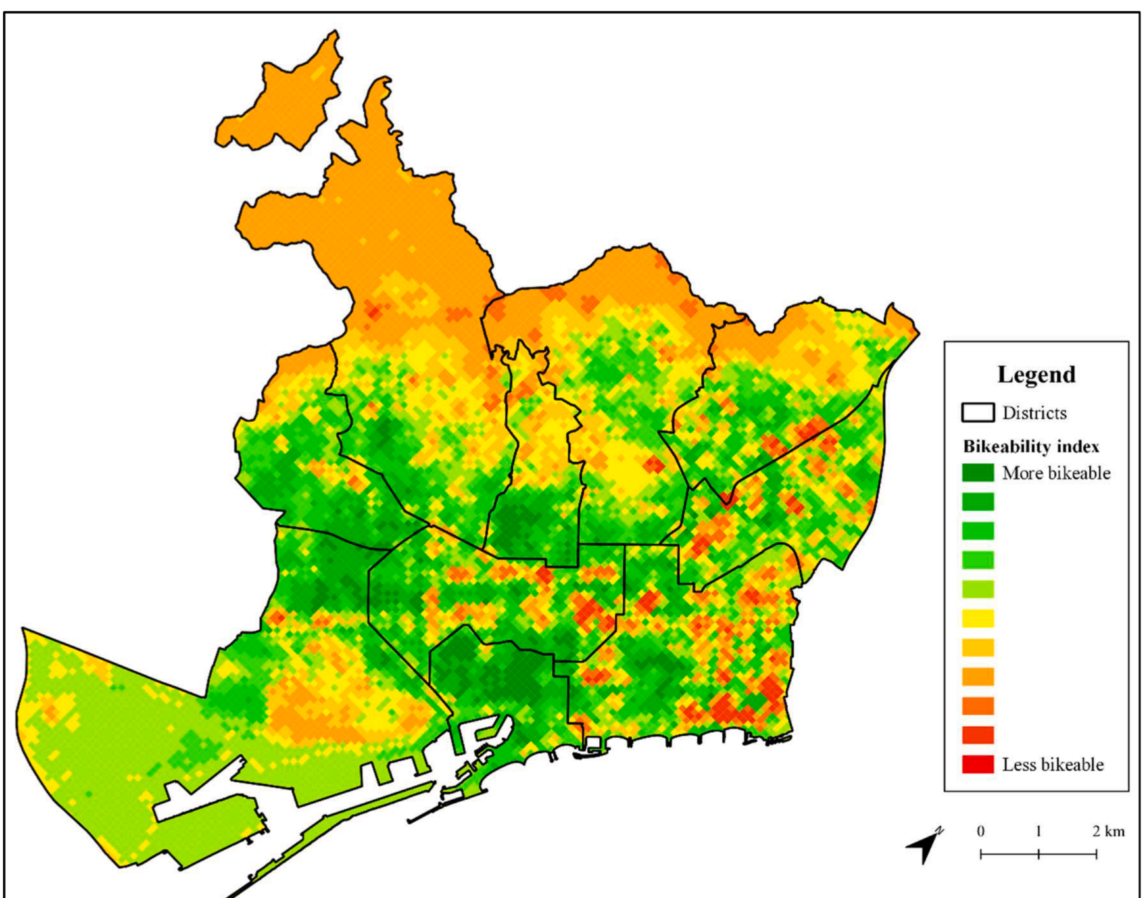
4.1. Bikeability index

When we assess the distribution of the bikeability index in Barcelona (Fig. 2) we can see that most built areas are bikeable, although a considerable number of spaces present some challenges. Areas in green are the ones that score well in the index and therefore have better conditions for cycling, while areas in yellow to red need improvement. The map shows significant disparities in areas in the city of Barcelona and makes it easy to identify those places where cycling can be problematic.

As we can see, hilly areas – Collserola, Montjuïc and Tres Turons – are some of the least suited for cycling. These areas perform well in one of the most important components of bikeability (Traffic), but the lack of flat areas and cycling infrastructure is detrimental to their overall score. On the opposite side, flatter, more coastal areas, as well as neighbourhoods with very small blocks and abundance of pacified streets, such as Ciutat Vella, Gràcia or the north-western part of Sants-Montjuïc, concentrate high bikeability scores. The map also highlights the existence of some problematic intersections. The intersections along the Diagonal Avenue, especially those in the centre of Eixample are critical, and the northern districts of Nou Barris, Sant Andreu and Sant Martí also have intersections that present more danger to cyclists than other parts of the city.

While the composite map is a great way of summarizing the information, it does not include the *nature* of the diversity in bikeability. In other words, it does not differentiate between the many problems that can affect the bikeability of an area. On the other hand, component maps, shown in Fig. 3, offer a much better insight into the potential and challenges that each area may face when evaluating its suitability for cycling.

In the spatial distribution of the variable “Traffic” we can see that overall, the city appears to be relatively safe for cyclists. The only areas where the interaction between cyclists and motorists are problematic are in the districts of Eixample and Sant Martí, which are also the districts with wider roads and more motorized traffic. This is especially true for the more central red area, in the vicinity of Diagonal Avenue and Gran Via. Meridiana Avenue, one of the main traffic arteries of the city, also



Source: Own elaboration.

Fig. 2. Bikeability index for the city of Barcelona.

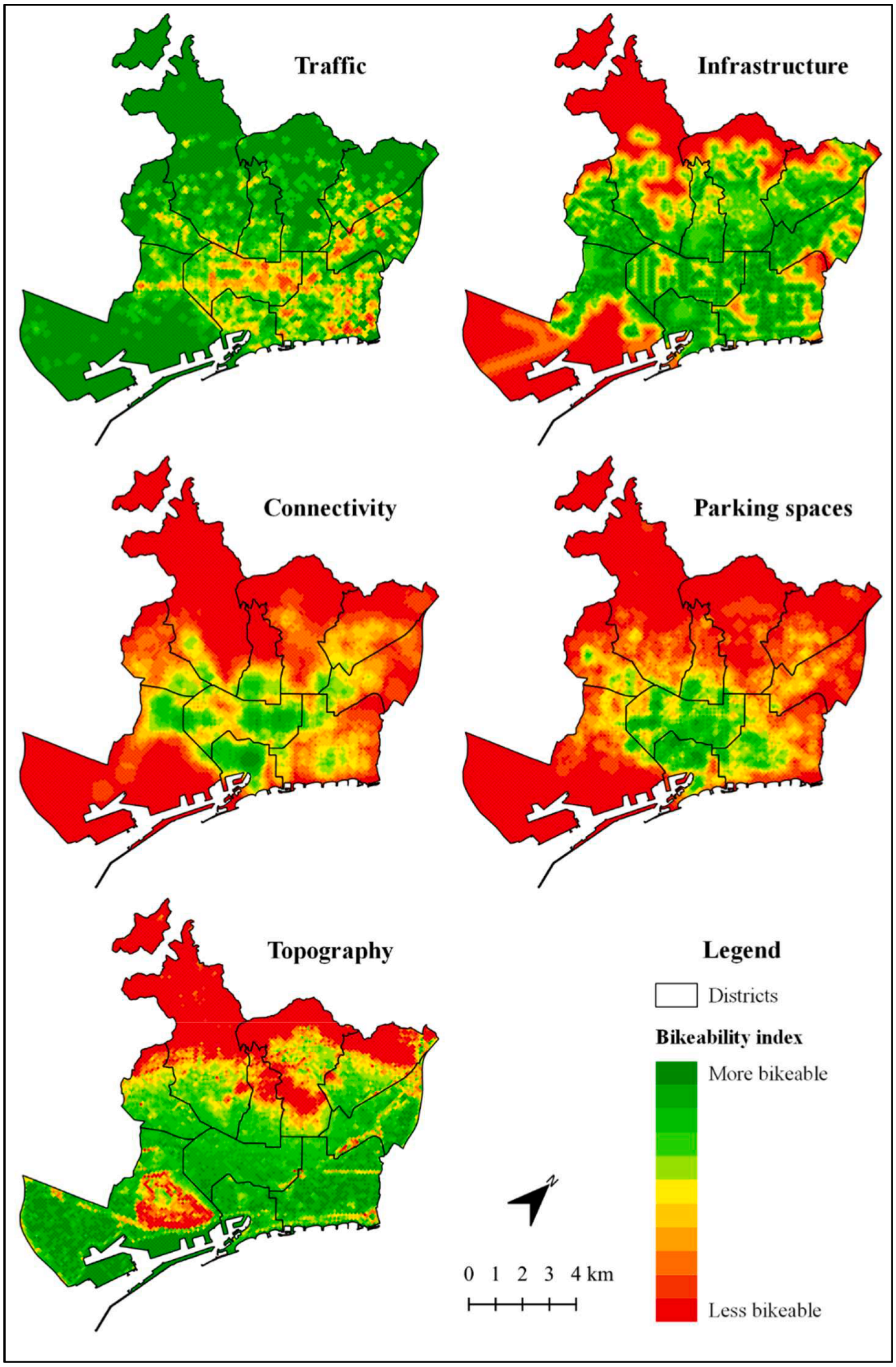


Fig. 3. Component maps of the bikeability index.

scores as a risky area, concentrating a higher frequency of accidents. However, Diagonal Mar, a recently-developed residential area located in the north-eastern part of the Sant Martí and away from the more congested streets, has a worrying number of collisions that calls for further intervention.

Collisions, however, cannot solely be attributed to a lack of infrastructure. As we can see on the "Infrastructure" map, most of the city is well provided of cycling infrastructure, except for the mountainous area of Collserola and the industrial area of Zona Franca, in the southern part of Sants-Montjuïc, as well as a smaller area near the northernmost area in Sant Martí. Except for the latter, these areas are scarcely populated, so it is understandable that the demand for cycling facilities there is lower. Nevertheless, the variable "Connectivity" nuances the real utility of the cycling infrastructure. Only a few areas in Eixample, Sants and Ciutat Vella stand out for having well-connected cycling infrastructure, while the rest of the city still has room for improvement.

As for "Parking Spaces", there is a lack of appropriate and dedicated parking spaces in vast areas of the city, as only Eixample and Ciutat Vella appear as areas where leaving the bike on the street is relatively easy. Even though some areas such as the hills of Collserola and Tres Turons as well as the industrial part of Zona Franca (southern Sants-Montjuïc) do not require large parking facilities because they are not residential areas, districts such as Nou Barris are heavily populated and yet there is a significant lack of bike racks or bike sharing systems.

Finally, the variable "Topography" confirms one of the main culprits of the lower bikeability score in some areas in places such as Montjuïc, Collserola or Tres Turons. The hilliness of the terrain makes it difficult for cyclists to climb. Nevertheless, we must bear in mind that Barcelona has an increasingly steepness from the sea to the mountain, which overall makes cycling a challenge for those living in the upper neighbourhoods.

4.2. Testing the predictive capacity of the index

To test the predictive capacity of our bikeability index, we use an official travel survey that asked about the frequency of cycling in the Barcelona area (n = 3620). Using the bikeability values within a 500 m network buffer from the geolocated address of each survey respondent we can observe a high association between bikeability values and frequency of cycling. Table 3 displays the average bikeability values around the residence of those who report biking always, almost always, often, sometimes, or never/hardly ever. The higher the bikeability index, the more frequent bike use is – a significant association that is confirmed by the ANOVA test further validating the predictive capacity of our bikeability index. This means that those living in more bikeable environments are generally more prone to cycling more often. Therefore, it confirms that a more bicycle-friendly environment helps increase the likelihood of cycling as a means of transportation.

Table 3 also includes the results for each of the individual indicators that compose the bikeability index. People who cycle more often do not necessarily seem to live in places where traffic interaction is safer. The same can be said about the distance to cycling infrastructure. Nevertheless, those who cycle often or almost always do tend to live in areas that have well-connected cycle infrastructure and that have more accessible parking facilities. This underlines the importance of a well-connected network to increase cycling, as well as having convenient places to park the bike, be it shared or private. When it comes to topography, it also appears that those living in flatter areas cycle more often. These results complement the aggregated bikeability index and show that bikeability does not come down to a single element of the built environment, but it is rather a sum of its parts.

Additionally, we have tested our index through a binary logistic regression model that adjusts for basic sociodemographic variables. In Table 4 we can see that a positive association between bikeability and the odds of being a frequent bike user exists (OR = 1.830; $p = 0.001$). The fact that most of the included sociodemographic variables are also statistically significant, suggests that they also have an influence on cycling rates.

Table 4
Binary logistic regression model assessing odds of being a frequent bike user per main socio-demographic and bikeability variables.

Variables	Exp(B)	Sig.	95 % CI	
			Lower	Upper
Socio-demographic variables				
Women[1]	0.390	0.000	0.327	0.465
Ages 30–64[2]	0.769	0.031	0.605	0.976
Ages ≥ 65[2]	0.345	0.000	0.206	0.580
Secondary education[3]	1.439	0.016	1.071	1.932
Higher education[3]	2.082	0.000	1.569	2.762
Unemployed[4]	0.939	0.688	0.689	1.278
Retired[4]	0.363	0.000	0.230	0.573
Homemaker[4]	0.518	0.136	0.218	1.231
Student[4]	0.808	0.301	0.539	1.210
Bikeability variables				
Bikeability index	1.830	0.001	1.300	2.576
Constant	0.367	0.000		

[1]Reference category = Men.
[2]Reference category = Ages 16–29.
[3]Reference category = No studies / primary education.
[4]Reference category = Occupied.

Our results show that there is an evident gender gap in cycling in Barcelona, as men are more willing to cycle for transport than women. Our model estimates that women in Barcelona have 0.39 the chance of cycling with respect to men. Young people (aged 16–29) are more likely to cycle than their older counterparts. This happens with adults aged 30–64 (OR = 0.769; $p = 0.031$), but more significantly with elderly people (OR = 0.345; $p = 0.000$).

Education level was used as a proxy for income and the results show that despite cycling is a very affordable means of transport, it is more prevalent among more affluent people. In Barcelona, people with higher education use the bike in a significant higher rate than people with elementary or no education (OR = 2.082; $p = 0.000$). Even people with secondary education also cycle significantly more (OR = 1.439; $p = 0.016$). Therefore, besides the gender and age gap, there is also a class and/or educational gap. The more educated a person is, the more likely they are to bike.

Lastly, when using job status as a sociodemographic variable, the results are not significant, except for retired people. However, we cannot infer that their lower likelihood for cycling (OR = 0.363; $p = 0.000$) is due to their condition as retired people. It is more likely that this is due to their age, as we have previously seen.

When including all the components of walkability along with adjusting for basic sociodemographic variables (Table 5) results do not

Table 3
Bivariate associatios between bikeability components and frequency of bike use.

Frequency of bike use[a]	Bikeability index		Traffic		Infrastructure		Connectivity		Parking spaces		Topography	
	Mean (SD)	p-value[b]	Mean (SD)	p-value[b]	Mean (SD)	p-value[b]	Mean (SD)	p-value[b]	Mean (SD)	p-value[b]	Mean (SD)	p-value[b]
		0.000		0.000		0.009		0.000		0.000		0.000
Never / hardly ever	0.170 (0.24)		−0.495 (0.66)		0.767 (0.36)		0.736 (0.85)		0.637 (0.92)		0.395 (0.51)	
Sometimes	0.191 (0.25)		−0.569 (0.66)		0.807 (0.30)		0.837 (0.88)		0.747 (0.93)		0.489 (0.44)	
Often	0.233 (0.28)		−0.586 (0.65)		0.783 (0.36)		1.001 (0.97)		1.004 (1.05)		0.496 (0.49)	
Almost always	0.227 (0.27)		−0.763 (0.75)		0.864 (0.20)		1.168 (0.90)		1.141 (0.92)		0.564 (0.43)	
Always	0.246 (0.33)		−0.563 (0.67)		0.749 (0.39)		0.963 (1.08)		1.064 (1.12)		0.540 (0.47)	
Total	0.179 (0.18)		−0.519 (0.66)		0.776 (0.35)		0.781 (0.87)		0.694 (0.94)		0.419 (0.50)	

[a] Self-reported frequency of bike use: *"Evaluate your use of cycling"*.
[b] One-way ANOVA test.

Table 5
Binary logistic regression model 2 assessing odds of being a frequent bike user per main socio-demographic and bikeability variables.

Variables	Exp(B)	Sig.	95 % CI	
			Lower	Upper
Socio-demographic variables				
Women[1]	0.386	0.000	0.323	0.460
Ages 30–64[2]	0.754	0.022	0.593	0.960
Ages ≥ 65[2]	0.331	0.000	0.197	0.557
Secondary education[3]	1.411	0.023	1.048	1.898
Tertiary education[3]	2.016	0.000	1.517	2.679
Unemployed[4]	0.925	0.624	0.678	1.262
Retired[4]	0.363	0.000	0.229	0.573
Homemaker[4]	0.530	0.152	0.223	1.264
Student[4]	0.768	0.203	0.511	1.153
Bikeability variables				
Traffic	1.007	0.933	0.851	1.193
Infrastructure	0.833	0.298	0.591	1.175
Connectivity	1.086	0.420	0.889	1.326
Parking spaces	1.180	0.052	0.998	1.394
Topography	1.344	0.025	1.039	1.740
Constant	0.361	0.000		

[1]Reference category = Men.
[2]Reference category = Ages 16–29.
[3]Reference category = No studies / primary education.
[4]Reference category = Occupied.

vary greatly compared to those with the aggregated index. Gender, age, and education remain significant predictors of cycling levels, while job status does not. Most of the individual components of bikeability are not significantly associated with the odds of being a frequent bike user. Topography is the only exception (OR = 1.344; $p = 0.025$), in a way that for every increase in 1 in our topography index (calculated in z values), there is a 1.344 increase in the likelihood of being a frequent cyclist.

5. Discussion and conclusion

The present analysis assesses cycling conditions in the city of Barcelona by creating and validating a new bikeability index. To do so we have used objective spatial indicators that stem both from the literature and a local survey on self-reported relevant factors for cycling in the city. The resulting index and distribution map has been later tested by using an official geolocated travel survey and has been validated as a predictor of bike use. The proposed index is thus both a valuable tool to represent the hotspots and problems of the capacity of Barcelona's built environment to sustain cycling, as well as to reliably predict the frequency of cycling. This index can therefore also be exported to other cities, especially with similar urban morphology features, such as those in the Mediterranean region.

Previous attempts to create bikeability indexes have tried to assign weights to spatial indicators based on theoretical criteria (Krenn et al., 2015b; Winters et al., 2013). The present analysis goes beyond that and similarly to Arellana et al. (2020), it wheights the variables by measuring their relative importance according to subjective data (the factors that are reported by local cyclists to be detrimental to cycling).

Bikeability indexes can often end up including too many variables leading to difficulties in interpretation or replicability for the general public, such as in the case of Lin and Wei (2018). Given the results of our study, we would argue that using some kind of validation criteria based on either self-reported barriers to cycling or on actual bike use would be more beneficial than trying to incorporate too many indicators. Bikeability indexes should be informative enough to pinpoint the main problems of cycling in a city as well as simple enough for them to be easily replicated elsewhere. Additionally, simplicity can also tolerate the inclusion of more place-specific variables better as each city can adapt the index to suit its own circumstances.

Previous research (Arellana et al., 2020; Kamel et al., 2020; Krenn et al., 2015b; Lin and Wei, 2018; Winters et al., 2013) had already shown that "bikeability" is a multidimensional concept that encompasses the sum of multiple factors. Our results confirm this as shown by the fact that the predictor capacity of the aggregate index was found significant while each of the individual components of the index did not. However, we have observed that some variables are indeed individually related with higher rates of cycling. For instance, people with nearby parking spaces have a higher probability of cycling, a phenomenon that had previously been hinted in Barcelona (Cole-Hunter et al., 2015). Nonetheless, it is topography the variable that consistently influences bikeability on its own in all our models. Our finding coincides with a wide array of previous research (Arellana et al., 2020; Cole-Hunter et al., 2015; Kamel et al., 2020; Krenn et al., 2015b; Lin and Wei, 2018; Winters et al., 2013), indicating the need to overcome the difficulties emerging from hilly terrain. Our finding is important as it demonstrates that objectively measured orography is having a negative effect over willingness to cycle. As e-bikes become more popular (Galatoulas et al., 2020; Roig-Costa et al., 2021) it is essential to continue monitoring the influence of this variable to bikeability. Hilly areas in Collserola, Tres Turons and Montjuïc are deemed particularly inappropriate for cycling. However, because these areas are relatively unpopulated areas and away from the main centres of economic activity, their impact on the city's overall daily mobility is rather limited.

Additionally, we have observed that presence of infrastructure and connectivity do not go together. No matter how good and safe cycle paths are, a poorly connected network eventually makes cycling less convenient, as it may force cyclists to take detours and leave designated bike paths, increasing the risk of accidents (Olmos et al., 2020). Bikeability indexes should thus consider connectivity indicators as basic core components, something that was already pointed out by Cervero et al. (2009) and Winters et al. (2013).

In Barcelona, the main deterrent factor is interaction with motorized traffic, and it is especially critical in the most congested streets, as well as the area around the eastern part of Sant Martí. This supports the need for providing infrastructure that not only enable cycling but also encourages it by making it safe and having cyclists perceive it as such (Handy and Xing, 2011; Parkin et al., 2007). Previous research such as Kamel et al. (2020) had already established that safety from motorized traffic was an important attribute to incorporate to the index, and our results fully agree with that assessment.

When it comes to sociodemographic groups we have also corroborated some points made in previous research. The gender gap in cycling, where women cycle less than men, has been observed in a myriad of studies (Handy and Xing, 2011; Ma and Dill, 2017; Mitra and Nash, 2019; Parkin et al., 2008; Van Dyck et al., 2013; Winters et al., 2007), and stands in stark contrast with the generally greater representation of women in active transport (Maciejewska and Miralles-Guasch, 2020). The cause of this inequality in cycling rates between genders has been widely discussed, but it can be attributed to insufficient access to dedicated bike infrastructure and a high presence of high-speed traffic (Mitra and Nash, 2019; Van Dyck et al., 2013). In a similar vein, young people are more likely to cycle than their older counterparts (Ma and Dill, 2017; Pucher and Buehler, 2008; Winters et al., 2007), a phenomenon that we have confirmed to also be the case in Barcelona. This may be attributed to the better physical condition of young people, but it can also respond to a generational gap, where younger citizens prefer alternatives to motorized transport for their daily mobility due to different factors, ranging from environmental concerns to a postponement of certain life milestones (Wang et al., 2018). On the other hand, education level was used as a proxy for income and the results show a paradox: despite the fact that cycling is a very affordable means of transport, it is more prevalent among more affluent people, as Ma and Dill (2017) and Parkin et al. (2008) already observed.

The present study is the first to map bikeability and its distribution in Barcelona. In this regard, other studies have worked on the city's walkability (Marquet and Miralles-Guasch, 2015) and vitality levels

(Delclòs-Alió and Miralles-Guasch, 2018). The spatial correlation between walkability and bikeability levels appears to be weak which is probably due to the incomplete network of dedicated bike lanes and uneven distribution of bike infrastructure. Bikeability seems to spatially correlate with urban vitality. When assessing bikeability levels, we must bear in mind that conditions might change throughout the day or the week. As Broach et al. observed (2012), traffic congestion can have enormous variations throughout the day, thus influencing the attractiveness of biking in certain areas at different times. Similarly, cycling has both utilitarian and recreational uses, and the consideration of what makes an environment “bikeable” may be different in both cases (Beenackers et al., 2012; Cervero et al., 2009; Kellstedt et al., 2021; Ma and Dill, 2017).

At the local level, the financial and political dimensions are crucial to increase its bikeability capacity (Alm and Koglin, 2022). However, city planners should be cautious when increasing levels of bikeability if they desire to increase cycling rates, as the attitudes, liking and comfort level with bicycling of the population are also important factors (Handy and Xing, 2011). This means that it is very difficult to change the willingness to cycle of a population just with infrastructure, there is a need to also change the attitudes and the mobility culture (Haustein et al., 2019). Therefore, the role of other forms of public policy is crucial in this sense, and a more comprehensive approach is highly recommended. Pro-bicycling initiatives, supportive land use planning and restrictions on car use are some of the complimentary policies that can help increase the number of daily cyclists and leave behind the marginalisation that bicycling once suffered in urban transport planning in comparison to other forms of transportation (Koglin, 2013; Koglin and Rye, 2014; Nielsen et al., 2013; Pucher et al., 2010; Pucher and Buehler, 2008).

6. Limitations

Our study is not without limitations. Our index only comprises the municipality of Barcelona, but the urban continuum of the city extends beyond its borders. When testing our index with the EMEF survey, we have considered the coordinates of the place of residence to see if cycling habits were greater in addresses with higher bikeability scores. It has often been discussed that eagerness to cycle is also dependent on the levels of bikeability of the origin, route and destination (Winters et al., 2010a).

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CRediT authorship contribution statement

Oriol Codina: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Monika Maciejewska:** Conceptualization, Data curation, Writing – review & editing, Funding acquisition. **Jordi Nadal:** Conceptualization, Writing – review & editing, Supervision. **Oriol Marquet:** Conceptualization, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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Data availability

Data will be made available on request.

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Ethics Approval and Consent to Participate

It is not applicable, because this manuscript does not report on or involve the use of any animal or human data or tissue.

Consent for Publication

It is not applicable, because this manuscript does not contain any individual person’s data in any form.

Availability of Data and Material

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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