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Title:

Measuring spatial inequalities in the access to station-based bike-sharing in Barcelona using an Adapted Affordability Index.

Abstract:

Bike-sharing schemes have been spreading globally during the last years. These should be publicly available schemes, servicing all groups of population. But the literature shows there are underrepresented population groups amongst their users. The physical access to bike-sharing stations and the supporting network of cycle lanes seems to influence the use of the schemes, especially of lower-income communities.

This paper applies an index as a tool to evaluate spatial inequalities in the access to station-based bike-sharing schemes and the cycle network. The index aggregates several variables related to the population level of affordability, including mobility-related variables. The Adapted Affordability Index was inspired in an existing one, produced by the city council, in an attempt to ensure its usability for policymaking. The index was calculated and applied to the case of the bike-sharing scheme in Barcelona, at the geographical level of census tracts. The index shows a strong correlation with income, a variable not always publicly available at such a small geographical level.

This study shows that there are inequalities in spatial access to the Barcelona bike-sharing scheme; the wealthier the population group, the more they have access to cycling infrastructure, especially to bike-sharing stations. The bike-sharing trend is accentuated in the hilly areas of the city.

The successful application of the Adapted Affordability Index to the city of Barcelona is a promising avenue to provide a robust and easy to use bike-sharing spatial equity evaluation tool for policymaking.

Keywords:

Bike-sharing; spatial inequalities; index; access; cycling infrastructure

Highlights:

- Spatial access to the Barcelona bike-sharing scheme *Bicing* is assessed for both bike-sharing stations and the cycle network.
- An Adapted Affordability Index is created in order to classify the population at the geographical level of census tracts.
- The Adapted Affordability Index strongly correlates with Income, which validates its use for social equity purposes.
- The wealthier the population, the more they have access to cycling infrastructure, especially to bike-sharing stations.
- wealthiest population in hilly areas have access to bike-sharing stations despite these being technically adverse locations.

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1 Introduction

The use of the bicycle for everyday mobility is on the rise in urban environments. One of the determinants for its use is the availability of a cycle network. This cycling-specific type of infrastructure is located in specific locations and spaces. The access to specific locations and spaces where cycling infrastructure can be found influences the mobility choices of city dwellers. Schemes that provide shared use of a bicycle fleet, or bike-sharing schemes (hereafter 'BSS'), facilitate the use of the cycle network by the population. Both the cycle network and BSS are considered cycling infrastructure, "hardware" that is used to support cycling mobility (Anaya-Boig, 2021).

Despite of the first BSS being implemented in Amsterdam in 1965 (Feddes, de Lange & Brömmelstroet, 2019), it was not until the following century that a new generation of BSS, generally operated via contact-less cards, began to appear in many cities and towns (Fishman, 2019). The academic interest in BSS has steadily increased over the last years, as review papers show (Fishman, 2016; Fishman, Washington & Haworth, 2013; Ricci, 2015; Si *et al.*, 2019).

BSS provide an active mobility option which, on the one hand, has a positive impact on individual health, mainly thanks to the benefits of physical activity; and on the other hand, it has public health benefits as a substitute for less sustainable mobility options (Rojas-Rueda *et al.*, 2011; Woodcock *et al.*, 2014).

Nevertheless, these benefits don't seem to be equally distributed amongst different population groups. Inequalities in the usage of BSS have been documented in Woodcock et al (2014), who found that the user profile of the BSS in London was predominantly male, white and employed. Additionally, studies in Australia and the United States showed than BSS users were younger, richer and more educated than the general population (Fishman *et al.*, 2014; Shaheen, Martin & Cohen, 2013). Race and income were analysed by McNeil *et al.* (2018) in a broad report about three cities with BSS in the US, showing that marginalised groups' barriers were bigger.

In her review, Ricci (2015) gathered evidence of how the differences usage is associated with an inequality of access to BSS from different cities in the world (Dublin, London, Montreal, Toronto, Salt Lake City, Minneapolis-Saint Paul, Mexico City, Beijing, Shanghai, Hangzhou).

The literature points out to the spatial distribution of BSS stations as a key feature to explain these inequalities in the usage of BSS (Clark & Curl, 2016; Ricci, 2015). As Clark and Curl (2016) explain, when all population groups have equal access to BSS stations, we would expect the proportion of the group which can access a station to equal that of the population as a whole. Where there are differences, this can be considered an indication of socio-spatial inequality of access and an indication of potential exclusion of some groups with respect to accessing BSS. Spatial access to BSS has been generally assessed in the literature by analysing the proximity to BSS stations. Howland et al. showed that the lack of BSS stations was an important barrier to the use of BSS in cities of the United States: 41% of operators "feel lack of bike infrastructure was a barrier to their potential users" (2017:pp.15–16). In a study sampling students in the University of Valencia, Molina-García *et al*., (2013) found than the most likely to become users were those who lived 250 metres or less from a BSS station. Similarly, Curto *et al.* (2016) found that the availability of BSS stations close to home was positively associated with bicycle commuting in Barcelona.

Studies that measure inequalities in the access to cycling infrastructures provide a description of the disparities between population with spatial access and population without spatial access to a service or resource, however spatial access is defined in each of the studies. This in itself, does not imply equity or fairness, however, a moral assumption can be made implying that unequal access to cycling infrastructure is unfair (Lucas *et al.*, 2019). Some studies show that some population groups would benefit more than others from having access to cycling mobility. For example, Teunissen *et al.* (2015) found that the Cicloruta bicycle network and Ciclovía recreational program in Bogotá (Colombia) do not offer equal access for all socio-economic strata (hereafter 'SES'), especially for the lower SES, however users mainly come from low and middle income SES. In other words, these lower income groups should have even more access to cycling infrastructure to achieve a fair or just state of affairs. García-Palomares *et al.* (2012) made an interesting contribution to this debate by assessing the two most commonly used location-allocation modelling for the city of Madrid, concluding that models with more uniform coverage are more equitable, compared to models that maximize potential demand. Even if there is no stated demand, it seems that the location of BSS stations in deprived areas could unlock a hidden demand and generate even bigger social benefits for lower-income populations. This would be supported by a study lead by Ogilvie and Goodman in London (2012), who found that people living in deprived areas, despite being less likely to live close to a BSS station, made more trips on average than people living in wealthier areas. The authors (ibid.) explained these findings in relation to the lack of bicycle ownership affordability (this was confirmed by McNeil, Broach & Dill, 2018) or storage facilities. Adding to the equity debate, McNeil *et al.* (2018) found that lower-income communities reported a greater need for stations than higher-income communities.

In terms of how to assess spatial access to BSS stations, Duran *et al.* (2018), in a study featuring five Brazilian cities, defined catchment areas using buffers around the BSS stations. In this study, researchers used publicly available household -level disaggregated data. Authors found that the mean income of the head of the household in the areas served by the BSS was 1.6 to 2.3 times the average of the cities'. They also found that the percentage of white residents in the cities BSS' catchment areas was almost twice as high as the cities' average. Using data from 29 BSS in the United States, Barajas (2018) also compared residents in service areas, this time defined as census units within 400 m of a bike-sharing station. The author found that BSS disproportionately served residential areas that are whiter, less poor and more proficient in English. Hosford and Winters (2018) compared residents inside and outside bike-sharing service areas in five Canadian cities. They used Dissemination Areas, the smallest spatial unit for which socioeconomic data is disseminated in Canada, located within 500 m from a bike-sharing station. Authors found that advantaged areas have better access to BSS infrastructure in four of the five cities. A recent study by Chen *et al.* (2019) located in southern Tampa (Florida, US), was able to capture disparities at individual level, thanks to their access to disaggregated data. Results show notable spatial disparities in the access to BSS stations (Gini coefficient higher than 0.95) and disparities amongst individuals of different socioeconomic groups categorized by race, income level and age.

The use of the bicycles of BSS requires appropriate infrastructures and spaces. This might seem obvious, but there are not many studies using both variables to assess bike-share use and even less to assess this in regard to equity. An exception is a BSS trip generation study in the city of New York, that found that the proximity of cycle lanes to BSS stations was associated with a greater use of the BSS (Noland, Smart & Guo, 2016). Studies assessing BSS performance acknowledge the need for these schemes to be integrated within the cycle infrastructure network. In Spain, a study in Valencia by Molina-García *et al.* (2013) concluded that a successful use of the BSS needed to be complemented with a cycle network. In line with previous observations by Midgley (2011) and also in Spain, Marqués *et al.* (2015) conclude that an integrated offer of cycling infrastructure (BSS stations and cycle network) was necessary to attract new cyclists in the city of Seville. The access to both BSS and the cycle network seems to be lower for disadvantaged communities, such as low-income groups and

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ethnic minorities, as shown by the results of a survey to BSS operators, the majority from the United States (Leister *et al.*, 2018).

Following Martens *et al.* (2019) principles for measuring transport equity, we argue that an unequal distribution of cycling infrastructure (BSS stations and the cycle network) sets the conditions for an inequitable allocation of cycling mobility resources. The aim of this study is to measure socio-spatial inequalities in the access to BSS by assessing the population in census tracts that have a station in their area against those that don't. Additionally, we acknowledge the importance of the spatial access to cycle lanes to support the use of the BSS by analysing first the integration between both networks (the BSS stations' network and the cycle network) and second the access to the cycle network.

The BSS "Bicing" used in the study is the one in Barcelona, Spain. It is a BSS with 419 stations and 6,000 bicycles in a city of 1,600,000 inhabitants. Launched in March 2007, "Bicing" is used 34,920 times per day. The total number of cycle trips in the city was 184,186 which corresponded to a modal split of 2.3% of all trips (Ajuntament de Barcelona, 2020b).

Geographic units (census tracts) were classified according to the different categories of an index especially created for this study and inspired in an existing one, used by the city council. The aim is to tackle the absence of BSS equity evaluation tools both in academic literature and in policymaking with the most transferable and easy-to-use index proposal.

2 Materials and methods

The aim of the study is to measure socio-spatial inequalities in the access to a BSS, including the cycle network that would support the use of the scheme. The cycling infrastructure networks that will be analysed are, on the one hand, the BSS stations' network and, on the other hand, the cycle network.

Assuming that the equal distribution of these two infrastructural elements facilitates cycling mobility in an equitable way, the subsequent equity analysis focuses on measuring the corresponding indicators in a disaggregated manner. The indicator for the availability of the BSS network and the cycle network is defined by a catchment area within and around the census tracts. The disaggregation used to differentiate population groups from each other is operationalised through an index specifically created for this study. The index was inspired in an existing affordability index used by the city council at a level of their districts and adapted to a smaller spatial unit (census tracts), thus improving its accuracy, and to the publicly available data. The affordability index reflects the distribution of income of the population living in the census tracts.

The index-categorised census tracts with access to both cycling infrastructures: BSS stations and cycle network, were compared with those without access in order to assess if different categories differ.

Finally, sensitivity analyses were performed in order to assess the definition of catchment area, the validity of the index against income and whether hilliness was a confounding effect.

2.1 Data preparation

In the absence of individual-level disaggregated data, as used in some of the studies mentioned above (e.g. Molina-García *et al.*, 2013; Curto *et al.*, 2016; Duran *et al.*, 2018), we used the smallest geographical unit for which population data was available for our research, census tracts, also called census areas in other countries. These geographical units were first mentioned in the Spanish Electoral National Law of 1877 (Government of Spain, 1878:pp.379–

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406). According to this law, census tracts should be relatively similar in terms of area and they need to have a clear delimitation. The law also establishes that census tracts need to be defined by the provincial office of the Electoral Census. In the city of Barcelona, the 1,068 census tracts range from 657 to 3,677 residents (mean=1,525; SD=357).

The cycle network spatial layer (Table 1) was created by selecting the existing cycle paths. The 176.6 km of cycle network included the "Green Belt" (in Catalan, "Ronda Verda", a regional cycle network within the province of Barcelona) and "Cycle lanes". Cycle lanes included non-segregated cycle paths on pedestrian areas and cycle tracks on the road, completely protected from the rest of the road users or semi-segregated, by using rubber pieces.

Table 1. Description of the Spatial information used in the analysis.

Spatial Information (geographic features)	**Source**
Census tracts Boundaries (polygons)	**ICGC (2017)[a]**
Cycle network (lines)	**Open Data BCN (2018)[b]**
Bike-Sharing Stations (points)	**Open Data BCN (2018)[c]**
Elevation model (Raster 2D)	**ICGC (2016)[d]**

Note: INE, Instituto Nacional de Estadística (National Statistics Institute); BCN, Barcelona; ICGC, Institut Cartogràfic i Geològic de Catalunya (Cartography and Geography Institute of Catalonia).

[a] ICGC provided the delimitation of the census tracts updated for Catalonia (https://www.icgc.cat/en/Public-Administration-and-Enterprises/Downloads/Geoinformation-layers/Census-sections)

[b] Open Data BCN (https://opendata-ajuntament.barcelona.cat/) information was provided by Barcelona City Council. The datasets included in the Cycle network were: "Ronda Verda" and "Cycle paths".

[c] Open Data BCN (https://opendata-ajuntament.barcelona.cat/) is provided by Barcelona City Council. The dataset was "Bicing stations location". Note that at the end of 2018 started a transition to a different technology and the number of stations is planned to increase during 2019 and 2020.

[d] ICGC provided a "Terrain elevation model" with a grid of 2x2 metres of resolution (https://www.icgc.cat/en/Downloads/Elevations/2x2-m-Terrain-elevation-model).

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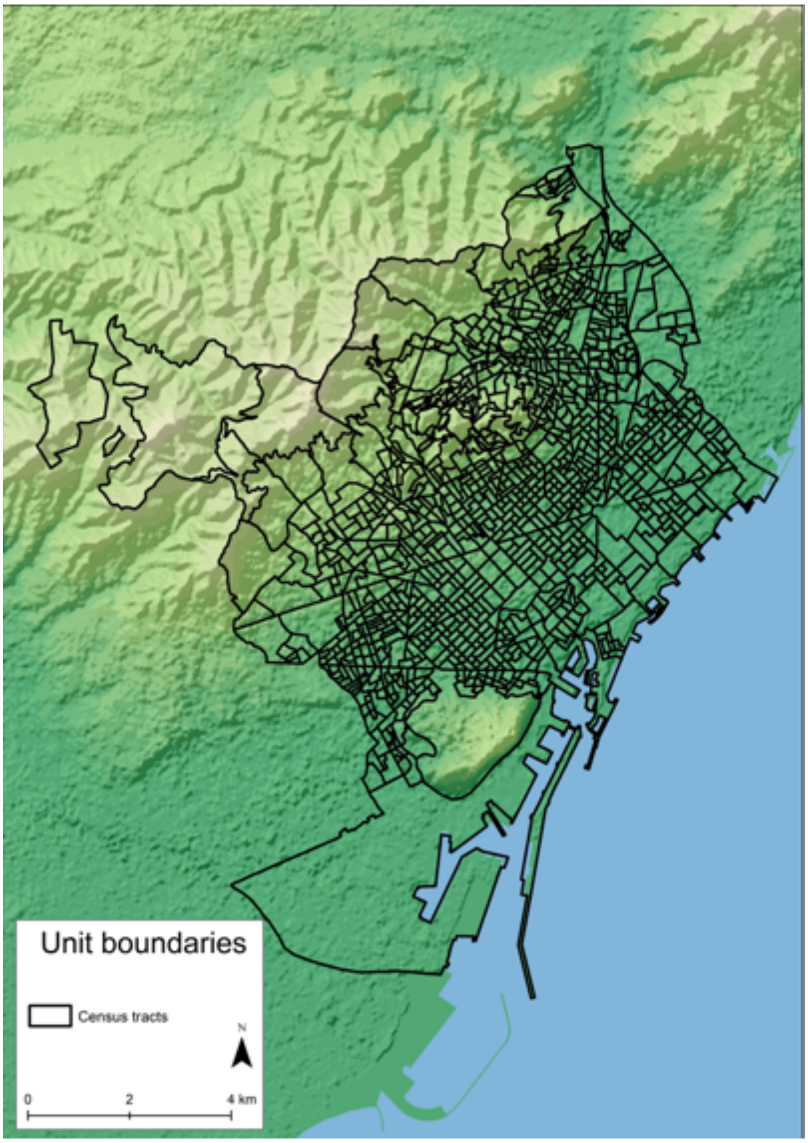

Figure 1. Map with topography and census tracts in Barcelona

The map in Figure 1 shows the census tracts delimitation in the city of Barcelona. The map also shows the land elevation or topography.

2.2 Adapted Affordability Index (AAI)

We propose an Adapted Affordability Index (hereafter 'AAI'). The AAI is an adaptation from an existing index designed by the Barcelona City Council, the "Household Income Index" – originally in Catalan "*Índex de Renda Familiar*" (Ajuntament de Barcelona, 2016). The main goal of the original index was to categorise the population in different groups, in relation to their level of affordability. The differences between these groups would help to illustrate social inequalities in a spatial context, measured against the averages of a specific population, in this case, the population of the city of Barcelona.

The reasons why we use the "Household Income Index" by the city council as a starting point are twofold: on the one hand, it features mobility-related variables that were appropriate for our study. On the other hand, this study aimes at producing easy-to-use outcomes for policymakers, hence the inspiration of an index that was created by policymakers for their own use.

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The only study that had assessed bike-sharing spatial equity using an index is the afore-mentioned Canadian-based analysis by Hosford and Winters (2018). The Pampalon Deprivation Index features material and social deprivation indicators (Pampalon *et al.*, 2012) but none of them are mobility-related and the authors did not adapted it for their study.

There are only two differences from the original definition of the city council's affordability index caused by data availability and the specific focus on mobility. One of the differences is that the city council uses a bigger geographical unit, the districts. We aimed at the smallest possible geographical unit and we found information at the level of census tracts for all the variables included in the city council's index except for the Proportion of unemployed population. We decided to use Census tracts in spite of losing one variable of the original Index. The other difference relates to the vehicle ownership, in this case, given that the information was available, we decided to account only for non-commercial vehicles in order to have a more accurate idea of mobility options unrelated to logistics.

The following table shows the details of the variables that were aggregated in the AAI and the extra variable Income, against which the AAI was tested for correlation as a sensitivity analysis.

Table 2. Description of the variables in the Adapted Affordability Index (AAI).

Data (per census tracts)	**Source**
AAI components	
Proportion of higher educated population [%]	**Ajuntament de Barcelona (2016)**[a]
Property value [€/m^2]	**Ajuntament de Barcelona (2016)**[b]
Proportion of high taxable horsepower automobiles [% automobiles with motor power above 16 HP of all automobiles]	**Ajuntament de Barcelona (2016)**[c]
Non-commercial vehicle ownership [number of automobiles per 1,000 inhabitants]	**Ajuntament de Barcelona (2016)**[d]
Sensitivity analysis	
Average Income per person (older than 15 years old) [€]	**INE (2016)**[e]

Note: AAI, Adapted Affordability Index; HS, horsepower; INE, Instituto Nacional de Estadística (National Statistics Institute).

[a] Reading of the Register of inhabitants of Barcelona City Council on the 1st of January 2016 (https://www.bcn.cat/estadistica/catala/dades/tpob/pad/padro/a2016/nivi/nivi11.htm)

[b] Local land value, Data from the Property Tax Database, Land registry/records office, Ministry of Economy and Finance, reading on January 2016. Provided by the City Council Finance Institute, Barcelona (https://www.bcn.cat/estadistica/catala/dades/timm/classol/locals/valor/a2016/VL04.htm).

[c] Taxable horsepower of automobiles. Vehicle census of Barcelona City Council, 2106 (https://www.bcn.cat/estadistica/catala/dades/economia/vehicles/a2016/potencia/t05.htm). The Tax to a vehicle of 16 or more taxable horsepower is at least 172 € per year, similar to the tax of a minibus or a medium-sized van (https://ajuntament.barcelona.cat/hisenda/en/ivtm-tax-mechanically-powered-vehicles).

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[d] Type of owner of automobiles. Vehicle census of Barcelona City Council, 2106 (https://www.bcn.cat/estadistica/catala/dades/economia/vehicles/a2016/propiet/t04.htm)

[e] Data from the National Institute of Statistics, 2016 (https://www.ine.es/jaxiT3/Datos.htm?t=30896#!tabs-tabla)

All the alphanumeric information described in Table 2 was associated to the geographical units - census tracts - and it was merged using ArcGIS software (ESRI, 2016).

The City Council of Barcelona applied weights in the calculation of the Index ranging between 17.5% and 15.0% and depending on the type of information provided by each variable. We decided to apply equal weights of the variables in the AAI calculations given that the difference between the weights was very small and the sources of the information were different.

As a data clustering method, the index was divided into 5 categories, using the Jenks natural breaks classification method (Jenks, 1967). The Jenks method optimises the accuracy in the visualisation of categories on a map statistically by reducing the variance within classes and maximising the variance between classes. This clustering method was calculated using ArcGIS (ESRI, 2016).

The city council index did not feature any income variable, which is widely used in equity analysis if available. This variable was not available at the level of census tracts at the time that the city council designed their index and we decided to replicate the limitations that the city council faced, in order to create an index that would still be valid to assess mobility equity in absence of the income variable. This way we also supported the transferability of the study, as income information might not be available or updated at the level of census tracts for other cities.

Furthermore, the recent availability of income data at census tracts level allowed us to perform a sensitivity analysis to check the validity of our results. The sensitivity analysis consisted of the calculation of the correlation between the AAI and the income variable.

2.3 Access to BSS

In order to assess the access to the BSS scheme, we have done three different analyses. The first one explores the integration of the BSS station network with the cycle network, applying a walking distance analysis. The second and main analysis of this paper defines the catchment area of both stations and cycle network and compares the AAI performance for the residents within and outside it. The third analysis examines whether the hilliness can be a confounding effect for the access to BSS stations.

2.3.1 The cycle network as a support for the BSS

We assume that the spatial access to the BSS is partly conditioned by the availability of a cycle network in which to use the shared bicycles. For this reason, not only we have analysed the access to the cycle network using the same conditions used to define the access to the BSS stations, but we have also analysed how the two networks are integrated in space. We have also assumed that the BSS users will cover the shortest distance between the BSS station network and the cycle network by walking, using the street network (not the Euclidian distance). We have calculated the average walking distance between the BSS stations and the cycle network for each of the index categories. A statistical test, a one-way ANOVA (Analysis of Variance) was used to assess whether there were differences between the categories.

2.3.2 Catchment area

The area in which population can physically access a station-based BSS is defined as the catchment area around BSS stations. This study focuses on residential population; thus, access to BSS stations is defined as the walking distance to and from stations from the residence location. When data are available at individual or household level, the geographical objects to analyse are "points". In this case, in the literature, BSS catchment areas are defined as buffers, and studies then compare the characteristics of the population in geo-located points within and outside these buffers. The radius of these buffers is usually defined by distance that the residents are willing to walk to the BSS stations, assuming they are all able to walk.

When individual, disaggregated data is not available, studies use aggregated data in areal units such as census tracts or neighbourhoods. In these other cases, the geographical objects to analyse are "polygons", and the literature is not consistent in the definition of the catchment area; there are studies that implement buffers (Smith, Oh & Lei, 2015; Hosford & Winters, 2018) and others that define catchment areas as those areal units with any station within their polygon (Brown *et al.*, 2019). Implementing buffers around polygons or just selecting those polygons that contain BSS stations both have limitations. Buffers add large amounts of area to the calculations by adding areal units with no stations where only a small part of the population has spatial access to the BSS. Selecting only stations contained in the polygons overlooks residents of neighbouring polygons that fall within walking distance from a BSS station.

This study uses aggregated data at census tract level and Barcelona is a relatively small city in terms of area (it has 101.4 km^2, with a shape of a triangle of about 11 km per side) with an exceptionally high population density (16.150 inhabitants per km^2). For this reason, implementing buffers of 400m or 500m as found in the literature for cities in the United States and Brazil, both for aggregated and disaggregated data (Smith, Oh & Lei, 2015; Hosford & Winters, 2018; Ursaki & Aultman-Hall, 2015; Duran *et al.*, 2018) around the 419 stations of the Barcelona BSS would cover the entire area of the city. Given these specific urban features, we decided to define the catchment areas by selecting the census tracts containing any station and to run a sensitivity analysis adapting the buffer methodology to the Barcelona context.

The access to cycling facilities has then been defined in spatial terms applying the following conditions:

- Bicycle-sharing stations (points) that were "completely contained" in the census tracts (polygons).
- Cycle network (lines) that "intersected" with the census tracts (polygons)

For a sensitivity analysis, the willingness to walk to a BSS station that defines buffer distances was calculated in relation to the density of the BSS station network. We argue that the average distance between neighbouring BSS stations influences the willingness to walk of the (potential) users of the BSS. If residents are planning to use the scheme, they will be aware of the location of the stations through the mapping services and the scheme app. Within the service area, that matches the municipality of Barcelona, residents have at least two stations at their reach; for this reason, we have assumed that they are not willing to walk more than half of the average distance between stations. We have calculated the average distance between closest stations applying a Nearest Distance Analysis using the software QGIS (QGIS Development Team, 2020).

To avoid the limitation of adding large amounts of extra area to the calculations, part of which would hold residents with no access to BSS stations, we applied an additional condition to the buffer-selected census tracts; they needed to be covered by the buffer in at least 50% of their area.

Hence, the definition of catchment areas for the sensitivity analysis is as follows:

- Bicycle-sharing stations (points) that were "completely contained" in the census tracts (polygons) or within a buffer of half of the average distance between neighbouring stations around the census tracts, when the buffer covers 50% or more of the area of the buffer-selected census tract.
- Cycle network (lines) that "intersected" with the census tracts (polygons) or with a buffer of half of the average distance between neighbouring stations around the census tracts, when the buffer covers 50% or more of the area of the buffer-selected census tract.

Hilliness is known to be a constricting factor for the use of BSS (Mateo-Babiano *et al.*, 2016; Sun, Chen & Jiao, 2018) and cycling infrastructure (Parkin, Wardman & Page, 2008; Vandenbulcke *et al.*, 2011). Previous studies of the Barcelona BSS show that cyclists are more inclined to avoid using stations located in elevated areas (Faghih-Imani *et al.*, 2017).

Even when it is used as a sheer technical limitation, this constriction might hinder the access to cycling facilities of population groups living in hilly areas. In other words, hilliness could work as a confounding effect; it is a technical explanation of the lack of stations in hilly areas, but it could also be related to the characteristics of the residents in these areas. For this reason, we decided to undertake a sensitivity analysis by stratifying the sample and analysing only the hilly areas (Bauman *et al.*, 2012).

The map in Figure 1 provides illustrative reference for the hilly areas in the city. For the sensitivity analysis, census tracts with hilliness were defined as those that had more than 5% of slope in at least half of their area. We found that 19 stations and 33.4 km of the cycle network are located in hilly census tracts.

In order to compare all the possible situations in terms of access to BSS stations and to the cycle network, six sub-groups have been studied; with and without access to BSS stations, with and without access to the cycle network, with access to both and with access to neither of them. For each of the sub-groups, the size and statistical strength of the difference between the AAI categories (first, for the general sample and second for the population living in hilly areas) was calculated with the Chi-Squared residuals and visualised in specific graphics. R Studio software (RStudio Team, 2018), with the package "corrplot" (Wei & Simko, 2017), was used to calculate and visualise Chi-Squared residuals.

3 Results

The first part of the results of this study was the calculation and visualisation of the Adapted Affordability Index at the level of census tracts.

The second part is the classification of the indexed census tracts according to their residents' access to cycling infrastructures. It also includes several sensitivity analyses.

3.1 Adapted Affordability Index (AAI)

The calculation of the AAI for the Barcelona census tracts produced five categories that are visualised in Figure 2.

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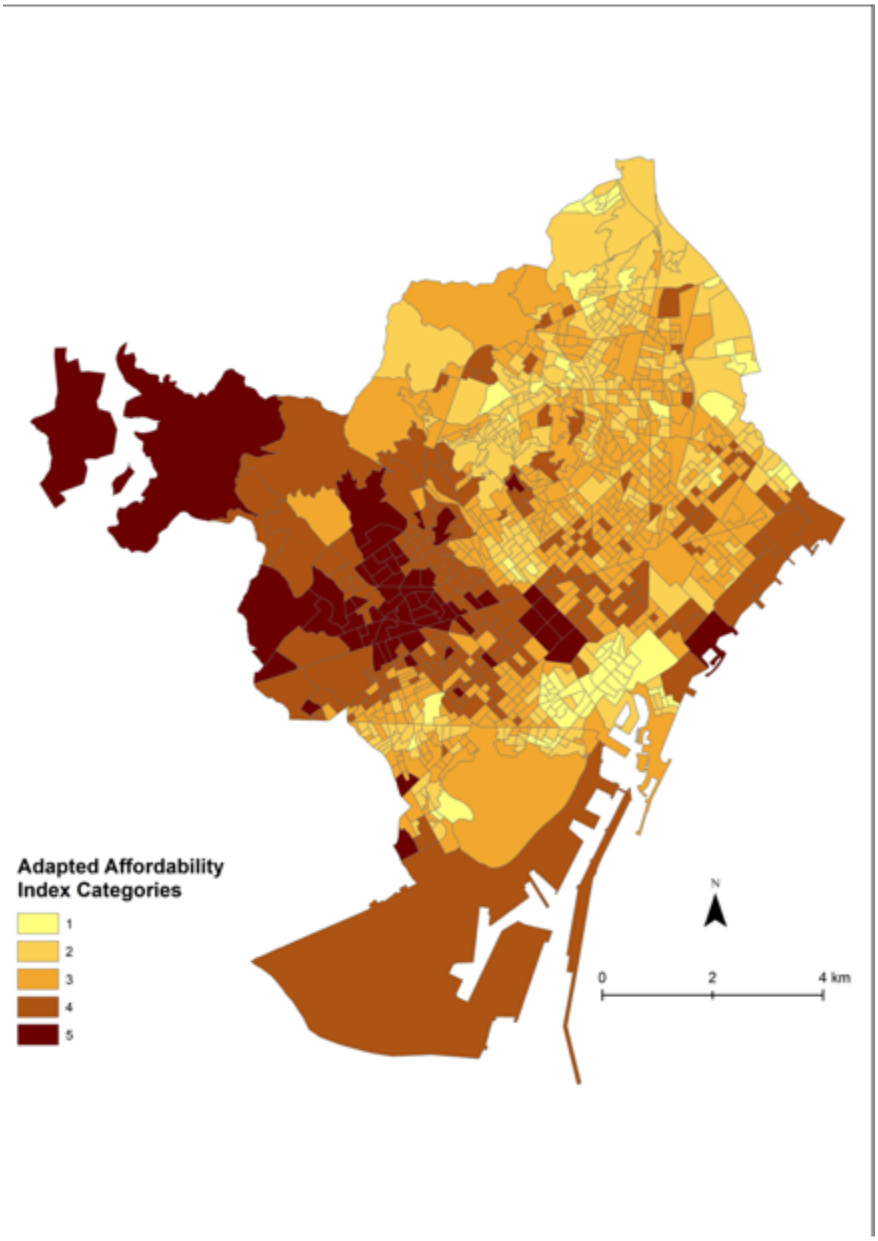

Figure 2. Adapted Affordability Index for the city of Barcelona

The AAI map in the figure above shows the distribution of the five categories in the urban space, ranging from category AAI 1 in yellow for the most deprived census tracts to AAI 5 in brown for the wealthiest and with AAI 2 in ochre, AAI 3 in orange and AAI 4 in brick red in between. Wealthier census tracts (AAI 4 and AAI 5) are mainly located in two areas: from the NW to the city centre and along most of the coastline. Deprived areas (AAI 1 and AAI 2) are mostly located in the historic city centre, close to the old docks. Census tracts of the lowest categories can also be found in areas to the NE and W of the city.

Sensitivity analysis with Income

In order to assess if the AAI was related to income, a correlation test was calculated. A positive correlation between the Adapted Affordability Index (AAI) variable and the Income variable was found. The linear correlation between the two variables was strong and statistically significant, $r=0.836$, $n=1,068$, $p < 0.01$.

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3.2 Access

3.2.1 The cycle network as a support for the BSS

To assess the integration of the BSS station network with the cycle network, the average walking distance between networks was calculated. Table 3 presents the average walking distance disaggregated by category.

Table 3. Average walking distance (metres) between BSS stations and cycle network, by AAI category

AAI Category	**N**	**Average distance (metres) (SD)**
Category 1	30	195 (190)
Category 2	69	220 (251)
Category 3	156	157 (204)
Category 4	104	170 (254)
Category 5	60	221 (217)
All categories	419	183 (227)

Note: AAI, Adapted Affordability Index; N, number of observations; SD, Standard Deviation.

As the Standard Deviation (SD) shows, there is a certain level of variability around the calculated means, especially in AAI 4. In terms of how the average distance differ between AAI Categories, a one-way ANOVA test determined that there were differences between group means ($F(4,414) = 1.49$, $p = 0.20$).

3.2.2 Catchment area

Of the total number of census tracts, 28.0% have access to BSS stations (Figure 3), 42.0% have access to the cycle network (Figure 4), 16.9% have access to both and 46.9% have access to neither stations nor the cycle network.

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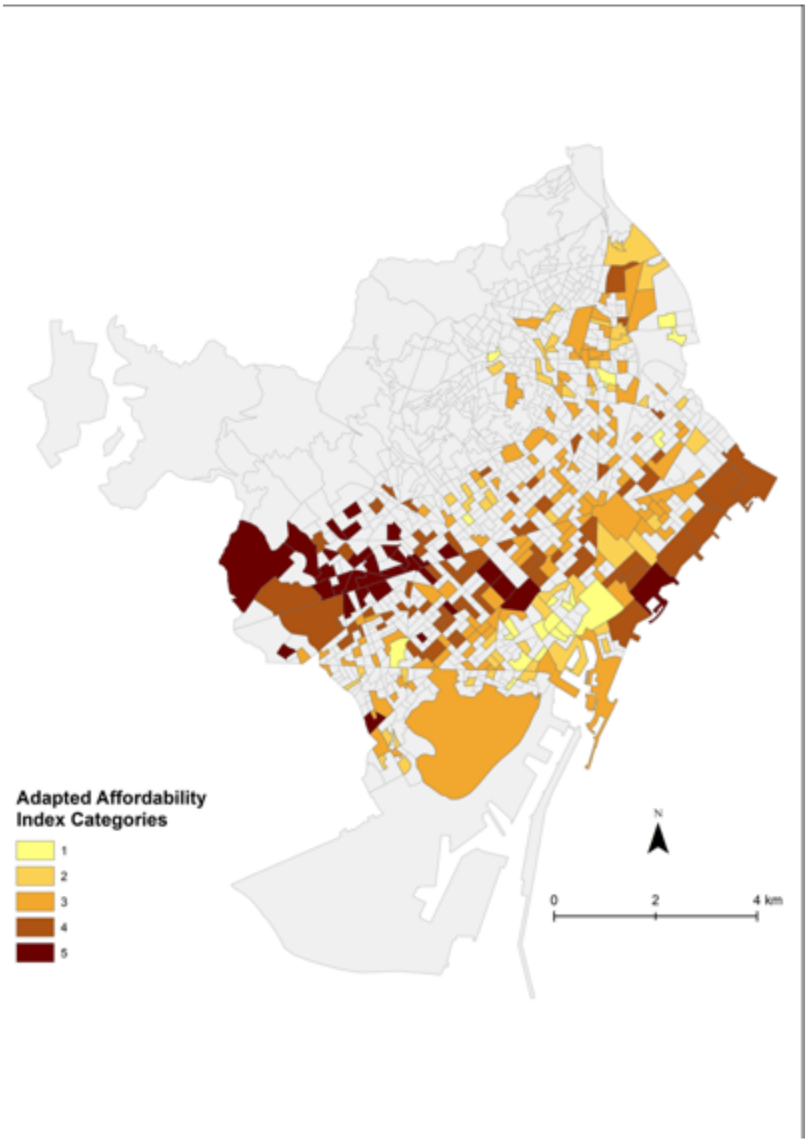
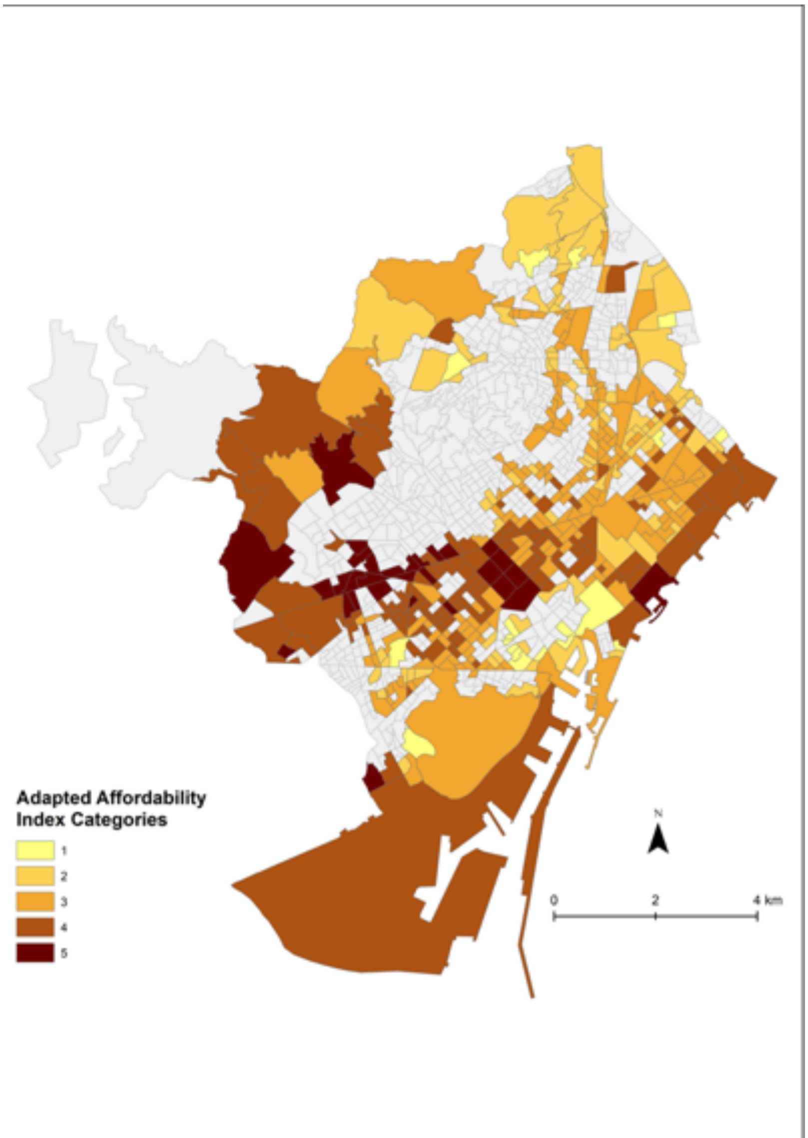


Figure 3. Census tracts with access to bike-sharing stations

DOI: https://doi.org/10.1016/j.jtrangeo.2021.103267



412
413 **Figure 4.** Census tracts with access to the cycle network

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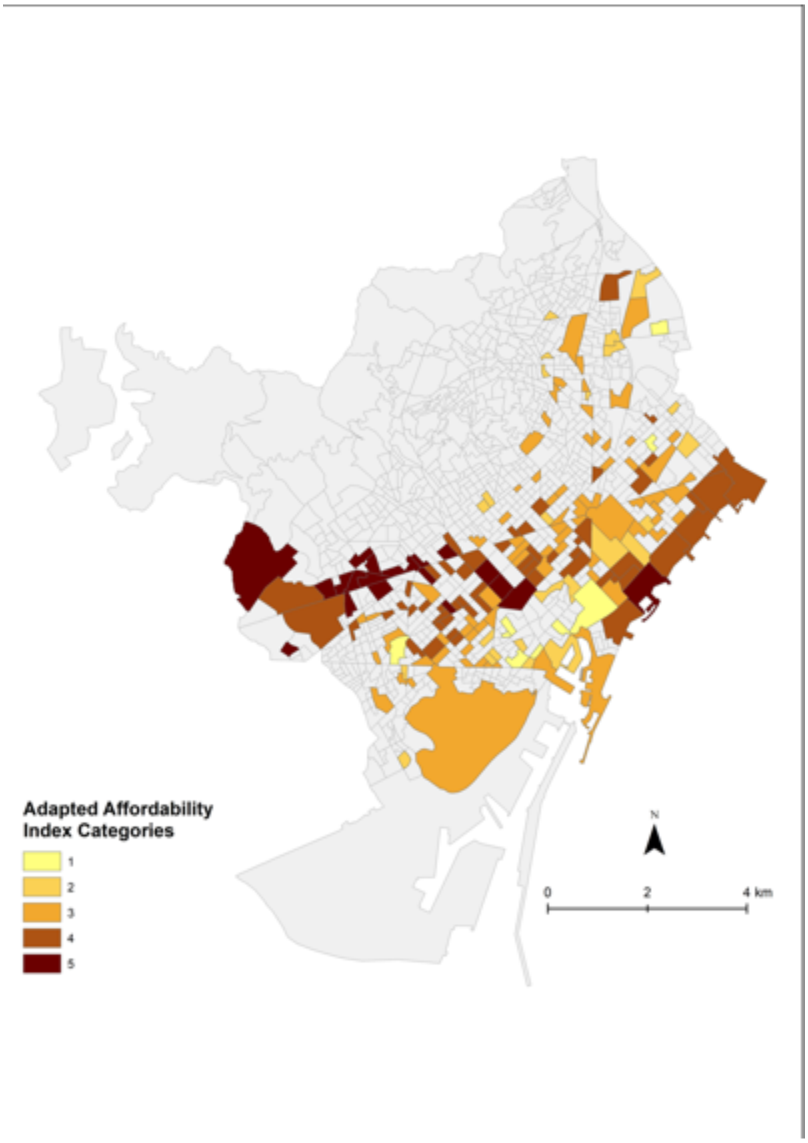

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415 **Figure 5.** Census tracts with access to both the cycle network and to BSS stations
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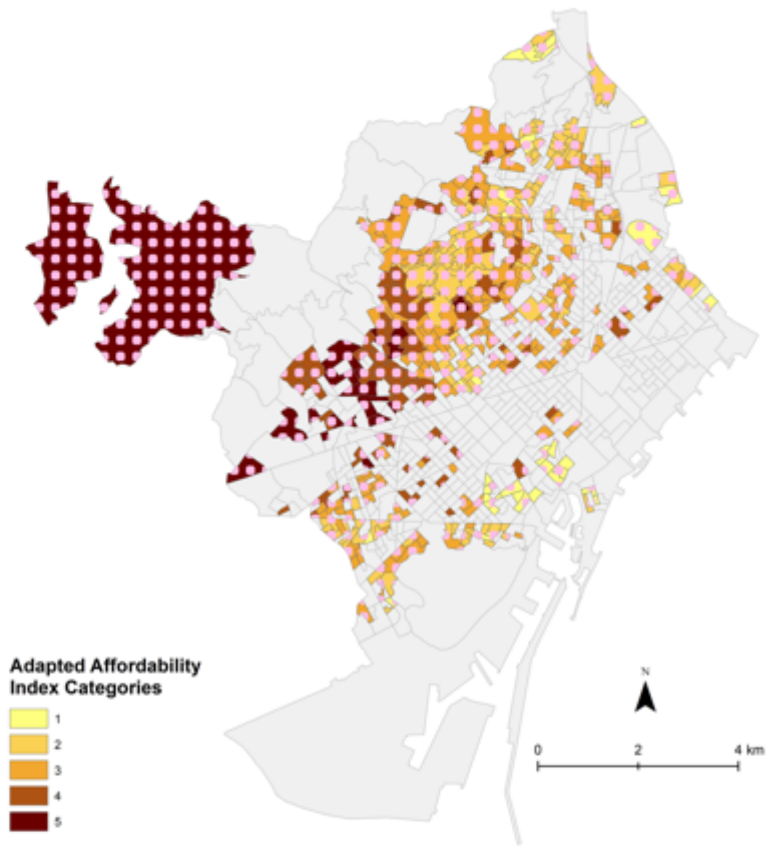

Figure 6. Census tracts without access to the cycle network and to BSS stations.

Census tracts with access to BSS stations are scattered due to stations being points geolocated at a certain distance between each other (Figure 3). There is a lack of stations close to the city administrative boundaries. These are, in general, poorer and industrial areas. The seafront is an exception to the absence of BSS stations in the boundaries. Coincidentally, it hosts high-value properties (Ajuntament de Barcelona, 2020a:fig.Lloguer Mitjà Mensual per Barris).

In contrast, census tracts with access to the cycle network show certain continuity due to the fact that they follow the lines of the cycle lanes and paths (Figure 4). However, the map also shows a gap without any cycling infrastructure in a considerable area of the city. Note that the over-printed pink dots are meant to differentiate that coloured units in this map indicate the opposite from the rest, a lack of access.

Census tracts with access to both BSS stations and to the cycle network are centrally located or in the seafront and other wealthy areas of the city. On the other extreme, the lack of access to neither cycle infrastructures is located in hilly areas and poorer census tracts.

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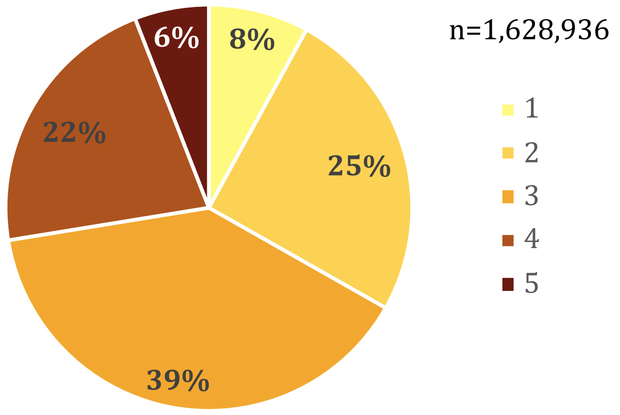

Figure 7. Total population split by AAI Category

The figure above presents the total population of the municipality of Barcelona split by AAI Category. Categories seem to be normally distributed, with the central category being the most populated and the poorest and wealthiest categories being the least populated.

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Table 4. Distribution of the total census tracts and population by Adapted Affordability Index Category and access to cycle network and to bike-sharing stations.

ALL CENSUS TRACTS			Cycle network				Bike-sharing stations				Both		None	
			No		*Yes*		*No*		*Yes*					
AAI Category	**Census tracts (%)**	**Total Population (%)**	**Census tracts (% All categories)**	**Population (% Category Total)**	**Census tracts (% All categories)**	**Population (% Category Total)**	**Census tracts (% All categories)**	**Population (% Category Total)**	**Census tracts (% All categories)**	**Population (% Category Total)**	**Census tracts (% All categories)**	**Population (% Category Total)**	**Census tracts (% All categories)**	**Population (% Category Total)**
1	73 (6.8)	129,995 (8.0)	54 (8.7)	94,773 (72.9)	19 (4.2)	35,222 (27.1)	53 (6.9)	94,322 (72.6)	20 (6.7)	35,673 (27.4)	9 (5.0)	18,037 (13.9)	43 (8.6)	77,137 (59.3)
2	271 (25.4)	411,027 (25.2)	185 (29.9)	274,492 (66.8)	86 (19.2)	136,535 (33.2)	218 (28.3)	322,698 (78.5)	53 (17.7)	88,329 (21.5)	25 (13.8)	45,763 (11.1)	157 (31.3)	231,926 (56.4)
3	424 (39.7)	638,924 (39.2)	235 (38.0)	342,959 (53.7)	189 (42.1)	295,965 (46.3)	306 (39.8)	451,356 (70.6)	118 (39.5)	187,568 (29.4)	73 (40.3)	119,956 (18.8)	190 (37.9)	275,347 (43.1)
4	236 (22.1)	352,695 (21.7)	111 (17.9)	162,875 (46.2)	125 (27.8)	189,820 (53.8)	160 (20.8)	233,242 (66.1)	76 (25.4)	119,453 (33.9)	54 (29.8)	86,370 (24.5)	89 (17.8)	129,792 (36.8)
5	64 (6.0)	96,295 (5.9)	34 (5.5)	49,027 (50.9)	30 (6.7)	47,268 (49.1)	32 (4.2)	45,737 (47.5)	32 (10.7)	50,558 (52.5)	20 (11.0)	33,590 (34.9)	22 (4.4)	32,059 (33.3)
All Categories	1,068 (100.0)	1,628,936 (100.0)	619 (58.0)	924,126 (56.7)	449 (42.0)	704,810 (43.3)	769 (72.0)	1,147,355 (70.4)	299 (28.0)	481,581 (29.6)	181 (16,9)	303,716 (18.6)	501 (46.9)	746,261 (45.8)

Note: AAI, Adapted Affordability Index

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The distribution of the AAI categories according to spatial access to the two types of cycling infrastructure (Table 4) shows that 72-73% of the most deprived communities lack of access in contrast to only 47-50% of the wealthiest. Communities scoring in the central to high AAI categories are the ones with higher access to both cycle infrastructures. Communities without access to neither cycling infrastructure are mainly those in AAI categories central to lower.

In line with the percentages of the population with access to both types of cycling infrastructure (Figure 3 and Figure 4), all categories show less access to BSS stations than to the cycle network.

It is clear for BSS stations that the wealthier the population, the more access they have to BSS. This is less clear for the cycle network, as only the two lowest categories had less than half of the population without access.

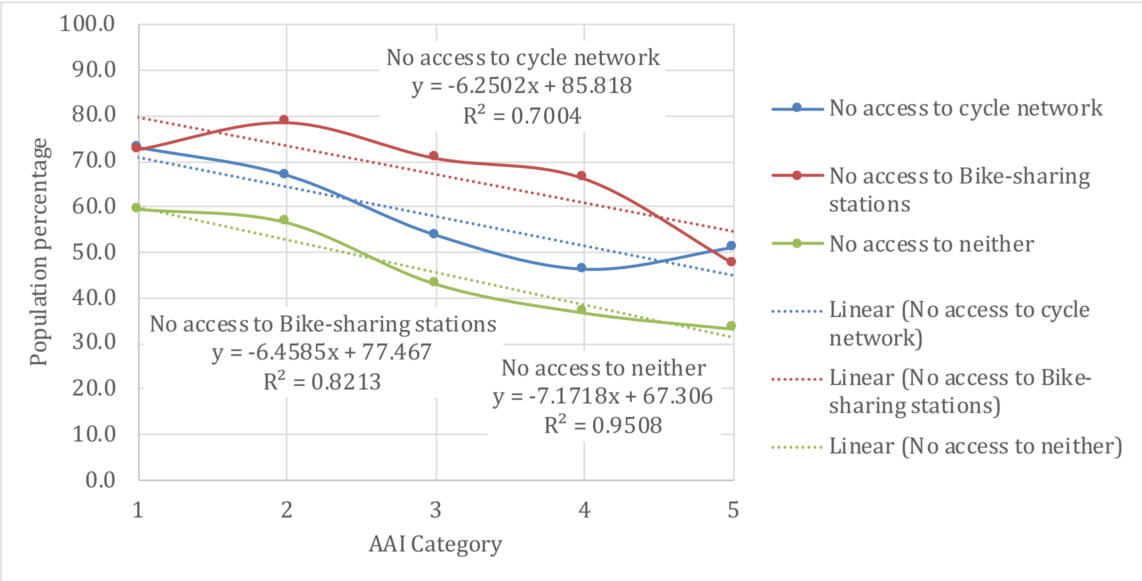

Figure 8. Percentage of population in each category with no access to cycle network and with no access to BSS stations. Linear regression equations and R-squared values displayed on chart.

In order to quantify the decrease of access to cycle infrastructure detected already in the description of the data, a linear regression was calculated for the population lacking access to each types of infrastructure and to both. The negative coefficients of the linear regressions for each of infrastructures were very similar (-6.25 and -6.46), which makes the two regression lines appear almost parallel. The relationship between complete lack of access and population was even steeper but in general, the rate of increase of access to both types of cycling infrastructures as categories became wealthier was similar.

The R-squared value for the lack of access to BSS stations was higher than for the lack of access to the cycle network, but they still explained 70% and 82% of the variance respectively. The goodness-of-fit of the linear regression between complete lack of access and population was the highest.

Extreme categories represented a similar percentage of population lacking access to both types of cycling infrastructure, but intermediate categories showed a relatively higher percentage of population lacking access to BSS stations than to the cycle network.

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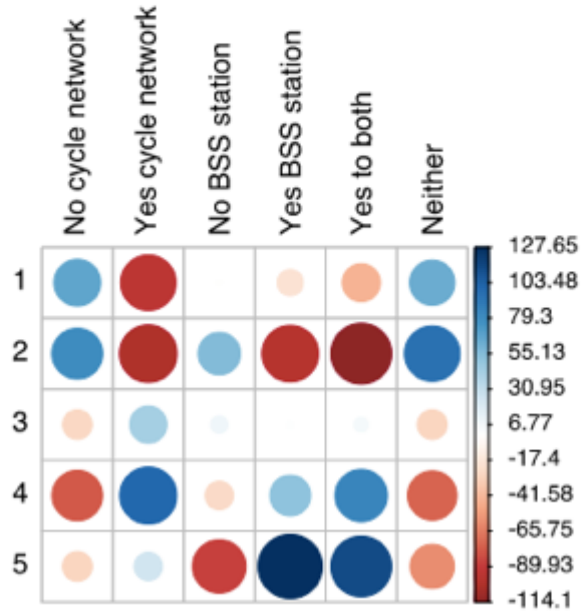

	No cycle network	Yes cycle network	No BSS station	Yes BSS station	Yes to both	Neither
1	**67.32**	**-94.94**	**-0.89**	**-20.23**	**-44.26**	**62.94**
2	**79.42**	**-102.3**	**55.05**	**-98.72**	**-114.1**	**94.88**
3	**-26.65**	**42.47**	**8.58**	**1.21**	**5.81**	**-26.93**
4	**-78.31**	**100.55**	**-24.63**	**51.19**	**83.95**	**-74.71**
5	**-27.07**	**24.41**	**-87.86**	**127.65**	**114.01**	**-59.93**

Figure 9. Residual plot of the Chi-squared Test of the AAI categories (1 to 5, in the y axis) of the population in all census tracts with (Yes) and without (No) access to the cycle network and BSS stations, access to both and access to neither of them.

A Chi-Squared test was calculated to observe the differences in the access to the cycle network and to BSS stations for residents in each of the categories (Figure 9). For a given cell, the size of the circle is proportional to the amount of the cell contribution. The contribution (in %) of a given cell to the total Chi-square score is calculated as the squared of the residual of the cell by the total Chi-square score: r^2/χ^2. Positive residuals are in blue and they show a positive association between the corresponding the specific AAI category and whether they have access to cycling infrastructure(s). Conversely, negative residuals are in red and they show a negative association. The vertical bar at the right side of the plot shows the numeric size of the residuals in correspondence to the colour range. The figure shows the plot on the left and the numeric results on the right, in the same grid.

The residual plot visualises and unveils the socio-spatial inequalities of the two cycling infrastructure networks:

- Population in census tracts with lower index values have significantly less access to both the cycle network and BSS stations.
- Population in census tracts with higher index values have significantly more access to both the cycle network and BSS stations.
- The population with more access to the cycle network are the residents in census tracts with AAI 4, whereas for BSS stations they are the residents in AAI 5, the wealthiest.
- The population with less access to the cycle network are the residents in the two lowest AAI, whereas for BSS stations it is the population in AAI 2 tracts.
- The wealthiest category of population had a disproportionate access to both cycle infrastructures.
- The lack of access to both cycle infrastructures was more evident for the second AAI category.

As a sensitivity analysis, the definition of the catchment areas based on census tracts was extended by buffers, under the condition of a partial coverage of the buffered census tracts.

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This analysis was motivated by the realisation that the density of the BSS station network in Barcelona BSS was higher than in the cities studied in the literature. For example, in cities in Brazil, the average distance between neighbouring BSS stations is about 500 m (Duran *et al.*, 2018) but in Barcelona is 170 m (this was calculated using a Nearest Neighbour Analysis). It was assumed that willingness to walk of potential BSS users would be half of the average distance between neighbouring stations, that is 85m.

To determine the catchment area of the BSS we applied 85m buffers around the census tracts' polygons, selected those that were covered by the buffer in more than half of their area, and run the analysis again. The number of census tracts of a total of 1,068 with access to BSS stations increased from 299 to 313 and for cycle network it increased from 449 to 493. This is a very small increase, that did not alter the results obtained for the non-buffered catchment area.

3.2.3 Hilliness

For a sensitivity analysis, only the subsample of the population living in hilly areas was used (Figure 10).

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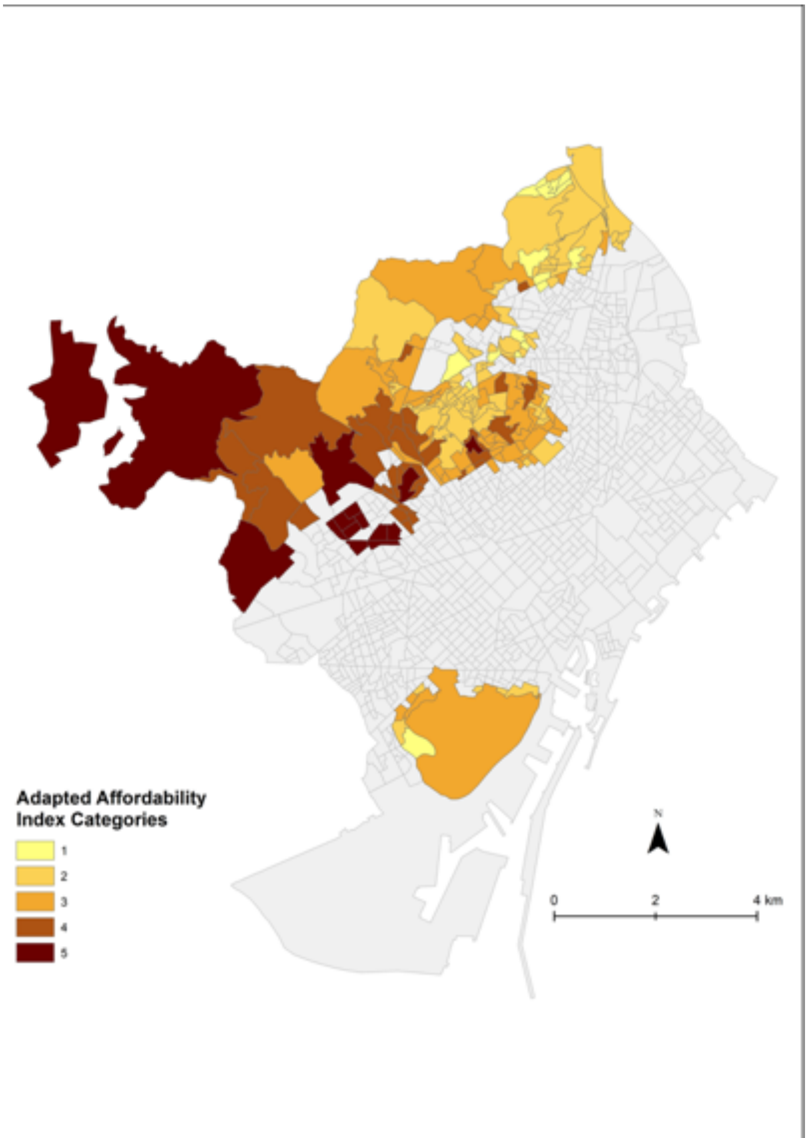

Figure 10. Census tracts with hilliness

Observing the map, it is not clear whether there are more residents of the poorer categories or of the wealthier categories living in hilly areas. This makes it difficult to conclude if the lack of cycling infrastructure in hilly areas is affecting all categories of residents equally.

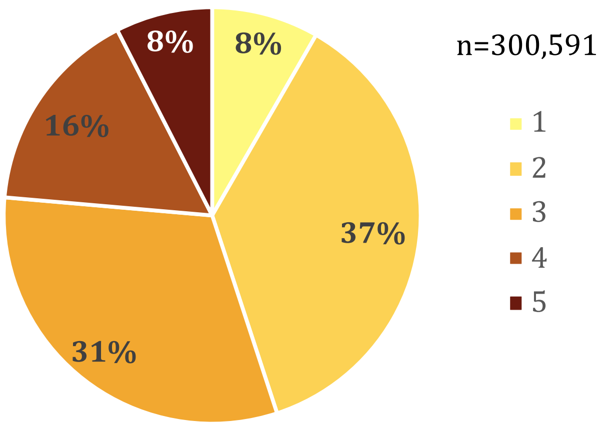

Figure 11. Population living in census tracts with hilliness split by AAI Category

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Unlike the total population shown in Figure 7, the population in hilly areas is not normally distributed by AAI categories; there is almost half of the population in the two most deprived categories.

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Table 5. Distribution of the population living in census tracts with hilliness by Adapted Affordability Index Category and access to cycle network and to bike-sharing stations.

CENSUS TRACTS WITH HILLINESS			Access to the cycle network				Access to bike-sharing stations				Both		None	
			No		*Yes*		*No*		*Yes*					
AAI Category	**Census tracts (%)**	**Total Population**	**Census tracts (% All categories)**	**Population (% Category Total)**	**Census tracts (% All categories)**	**Population (% Category Total)**	**Census tracts (% All categories)**	**Population (% Category Total)**	**Census tracts (% All categories)**	**Population (% Category Total)**	**Census tracts (% All categories)**	**Population (% Category Total)**	**Census tracts (% All categories)**	**Population (% Category Total)**
1	16 (8.0)	24,972 (8.3)	12 (6.6)	20,046 (80.3)	4 (11.1)	4,926 (19.7)	15 (8.0)	23,224 (93.0)	1 (7.1)	1,748 (7.0)	0 (0.0)	0 (0.0)	11 (7.1)	18,298 (73.3)
2	74 (36.8)	111,737 (36.7)	62 (34.3)	93,234 (83.4)	12 (33.3)	18,503 (16.6)	73 (39.0)	110,107 (98.5)	1 (7.1)	1,630 (1.5)	0 (0.0)	0 (0.0)	61 (39.4)	91,604 (83.1)
3	63 (31.3)	92,898 (31.4)	51 (28.2)	76,046 (81.9)	12 (33.3)	16,852 (18.1)	57 (30.5)	83,659 (90.1)	6 (42.9)	9,239 (9.9)	3 (75.0)	4,761 (5.0)	48 (31.0)	71,568 (75.8)
4	34 (16.9)	48,372 (16.1)	29 (16.0)	41,595 (86.0)	5 (13.9)	6,777 (14.0)	33 (17.6)	46,963 (97.1)	1 (7.1)	1,409 (2.9)	0 (0.0)	0 (0.0)	28 (18.1)	40,186 (83.1)
5	14 (7.0)	22,612 (7.5)	11 (6.1)	17,073 (75.5)	3 (8.3)	5,539 (24.5)	9 (4.8)	14,806 (65.5)	5 (35.7)	7,806 (34.5)	1 (25.5)	1,799 (8.0)	7 (4.5)	11,066 (48.9)
All Categories	201 (100.0)	300,591 (100.0)	165 (82.1)	247,994 (82.5)	36 (17.9)	52,597 (17.5)	187 (93.0)	278,759 (92.7)	14 (7.0)	21,832 (7.3)	4 (2.0)	6,560 (2.2)	155 (77.1)	232,722 (77.4)

Note: AAI, Adapted Affordability Index

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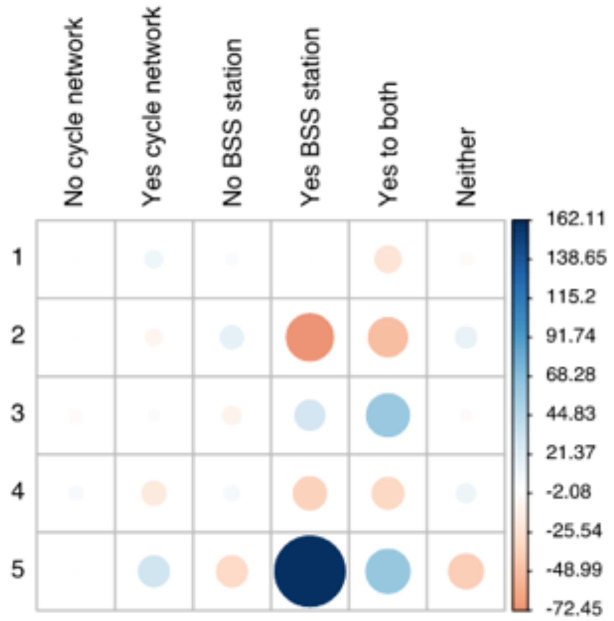
As expected, because of the technical constrictions of placing BSS stations in hilly areas and the lower preference of cyclists to use these areas, the percentage of population without access to cycling infrastructure (Table 5) was higher than for the whole city (Table 4).

However, the wealthiest category presented the highest percentage of population with access to each types of cycling infrastructure. This difference was more evident for BSS stations, with more than a third of the wealthiest group of population living in hilly areas having access to BSS stations.



	No cycle network	Yes cycle network	No BSS station	Yes BSS station	Yes to both	Neither
1	-0.63	10.03	3.92	-0.59	-23.08	-4.35
2	0.87	-8.65	17.34	-72.45	-49.59	14.76
3	-4.67	3.5	-11.13	29.45	60.03	-3.76
4	5.93	-19.36	7.26	-36.01	-32.69	11.66
5	-0.51	31.57	-32.14	162.11	63.19	-39.57

Figure 12. Residual plots of the Chi-squared Test of the AAI categories of the population in hilly census tracts with and without access to the cycle network and Bike-sharing stations, access to both and access to neither of them.

The residual plot highlights the difference in the access to BSS stations, with the wealthiest category (AAI 5) being clearly favoured and poorer category AAI 2 being disadvantaged. As shown in the numeric results, the effect for the access to BSS stations of people in AAI 5 is more than twice as big as the effect of lack of access for those in AAI 2. This effect is similar to the population with access to both infrastructures, adding a more perceptible positive effect for the middle category AAI 3. Those with lack of access to both types of infrastructure still show some effect favouring category AAI 5 and disfavouring category AAI 2.

4 Discussion

This paper presents an index as a tool to evaluate spatial inequalities for BSS and applies it to the case of the BSS in Barcelona. This study shows that there are inequalities in the spatial access to the Barcelona BSS and validates the index as an evaluation tool for policymaking.

The design and calculation of an Adapted Affordability Index from an existing one, produced by the city council, have been tested as a potential evaluation tool. The AAI index improved the geographical detail of the city council's by using the smaller units census tracts. Furthermore, the correlation with the variable income proved that the index was valid as a measure of social inequalities and reinforced transferability potential to cases with no or out-of-date income data.

The average distance between BSS stations and the cycle network is close to 200 m across Barcelona but there are differences between categories, which is later illustrated by the slightly unequal access to each of the networks by residents, especially those in extreme categories.

The distribution of the five categories of the index unveiled disparities in the access of the different population groups to cycling infrastructure. In the poorest categories, around three quarters of the population lacked access to cycling infrastructure, whereas for the wealthiest categories, the percentage of population with and without access is similar. That is to say, the wealthier the population, the more access they have to cycling infrastructure, especially to BSS stations.

The comparison of six sub-groups of population– with and without access to both BSS stations and to the cycle network, with access to both and with access to neither of them – with the total population showed differences in some of the categories. The size of these differences, expressed with the Chi-squared residuals, was especially notable for the access to bike-share of the wealthiest category. The lack of access was more evident for the two poorest categories, for the cycle network and for category AAI 2 for BSS stations. Population with access to both types of infrastructures was disproportionally wealthier (category AAI 5), whereas population without access to neither of them was disproportionally poorer (categories AAI 1 and AAI 2).

To explore the potentially confounding effect of hilliness, a sub-sample of the hilly areas was studied. The access to BSS stations shows the biggest effect in inequalities, with the wealthiest population category AAI 5 having much better access to BSS stations, even when there was a higher percentage of poor population living in hilly areas than in the whole city. Although this study does not assess cycling demand, it shows the unequal distribution of the BSS service, even in areas with potentially lower demand due to hilliness.

The results of the hilliness sensitivity analysis uncovered the contrast between a technical guideline – and research evidence - suggesting the avoidance of hilly areas for the location of cycling infrastructure, with other decision-making processes that result in the opposite, favouring the wealthiest population groups and exacerbating inequalities. The high level of access of a specific group in comparison to others should be regarded as a flow in the implementation of a public policy; which instead of being as universally accessible as possible (Beroud & Anaya, 2012), is favouring the wealthiest population group.

The study was not exempt of limitations. Census tracts are the smallest geographical units with useful information for these calculations. Nevertheless, the use of census tracts to account for population physical access had some limitations. We did not account for the exact population location, and the distribution of population within the area of the census tract might not be homogeneous. Household-located information, which is point-based, would have allowed the use of buffers to estimate the level of access to infrastructure, as other studies have shown (Duran et al., 2018), but this was not available.

It is also worth noting that we were not accounting for all the population that could potentially use the bike-sharing scheme, as we didn't include non-resident population in this analysis. This prevented us to analyse the potential inequalities in the access of the BSS as the "last-mile" of non-residents' trip chain. We did not have access to the appropriate information that would have been required for this type of analyses. In parallel, we assumed all residents were willing and able to use the cycling infrastructure, which might not have been the case because of not having the skills, capacities or willingness to cycle.

However, our study has noticeable strengths. In a broad sense, the use of an index allowed us to represent the complexity of spatial equity in an aggregated way. Thus, it is an easy-to-use evaluation tool for policy-makers, with potential practical applications to manage access inequalities to cycling policies.

Instead of assessing how BSS' infrastructure attracts potential and actual users, our study focused in assessing inequalities of BSS from the users' perspective, exploring the potential cycling mobility demand of the city dwellers. By doing this we moved from a mobility-centered approach to an accessibility-centered approach (Martens, 2019), and we applied this to BSS. As Martens posits "accessibility measurement is not merely an option but an absolute necessity", if decision-makers want to take the interests of persons seriously in the design of transportation systems (2019:p.28).

In order to make it as transferable as possible, the index was designed to be used in the absence of income data, but it was validated with a strong correlation with the income variable. It was a priority that the data used for the construction of the index was generally available and easy to find for city councils. The AAI was designed in a way that it could also be applied to bigger geographical units, in case it was necessary.

A distinctive feature of this study is the definition of buffer distance used in the sensitivity analysis, which can influence future studies using both individual-disaggregated data and areal-aggregated data. This distance is equivalent to an estimation of the willingness to walk to a BSS station and is defined in relation to the density of the BSS station network and conditioned by local urban features such as dimension of the service area (in this case, corresponding to the city boundaries).

The AAI includes mobility-related variables. High taxable horsepower automobiles are usually bigger in size than automobiles with lower horsepower but more expensive to own and maintain. Although there is not a definition of SUV (Sports Utility Vehicle) in terms of their horsepower, we assume that part of these high taxable horsepower automobiles can be considered SUV. The SUV segment is on the rise at least in Europe and it's replacing smaller utility vehicles (Mock, 2020). This is contributing to transport inequalities (Antal, Mattioli & Rattle, 2020), which makes it an important variable to feature in this type of analyses.

Furthermore, the issue of car ownership is becoming complex with the increase of shared mobility options, which could be understood as part of Mobility as a Service (MaaS). BSS can be part of MaaS, actually as Cycling as a Service (Petzer, Wieczorek & Verbong, 2019). These considerations would support the possibility of including these shared mobility options in future studies. Clark and Curl (2016) already studied the access to both services, bicycle and car share, in the same study, but more research is needed to properly understand the potential equity impact of car sharing schemes (Tyndall, 2017).

This study presents the AAI and applies it in one case study, but more case studies are needed in order to assess the applicability of this evaluation tool to a variety of situations. One of the goals of this study was also to produce an evaluation tool that policymakers and practitioners could use, but it has not yet been used by them, whose feedback could be critical in the improvement of such tool.

All data used in this study was collected before the Barcelona BSS, "Bicing", changed of contract holder. This change implied a change in the technology, including a bigger share of electric bicycles in the fleet, and an extension of the scheme to other parts of the city where it had not been before. This could have facilitated cycling in hilly areas and expanded the catchment area of the scheme. An updated analysis after these changes would help to assess whether the inequalities detected in this study have attenuated and provide valuable information for BSS design and planning.

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5 Conclusions

The index presented in this paper uses the available data to produce both a rigorous and an usable means for policymakers to calculate distributional inequalities in the access to BSS. Practical, easy-to-use evaluation tools are needed in order to assess bike-sharing inequalities in different cities. Adding to the existing literature, this paper focuses in a densely populated city of southern Europe, Barcelona. Confirming the existing inequalities and the need to integrate the access to the cycle network and use local indicators to produce more accurate results, such as hilliness and a network-based willingness to walk concept.

Results show that policies in relation to the promotion of cycling are failing to reach the most deprived areas in Barcelona, where poorer population live. Redistributive policies should prioritise the access to BSS and to the cycle network of poorer population groups, known to obtain greater societal benefits from this access than wealthier ones such as facilitating their social mobility and access to labour, education and health services.

Not only that, but governments should investigate why the wealthiest population groups, including those living in technically adverse (hilly) areas, are given more access to BSS stations than the rest of the population. Decision-making processes in relation to the location of stations and other features of BSS need to improve their governance and democratization in order to produce more equitable outcomes.

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