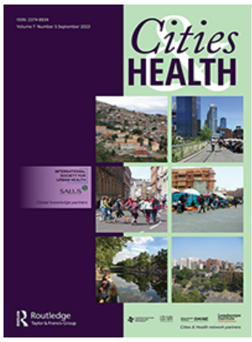

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ORIGINAL SCHOLARSHIP

Cycling infrastructures and equity: an examination of bike lanes and bike sharing system in Lisbon, Portugal

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ABSTRACT
Inequity of access to the cycling network may reinforce social disparities in health and access to resources and opportunities. This study aims to examine whether the area-level material deprivation index is associated with different levels of accessibility to Lisbon's (i) cycling network and (ii) bike-sharing docking stations network. Independent *t*-tests were implemented, and regression models were performed to estimate the associations of the multiple deprivation index with each dependent bike lane and bike-sharing docking station variable, adjusting for covariates. The results confirm the hypothesis of a significant difference between the most and least deprived areas in terms of the presence of bike lanes and bike-sharing stations as well as in terms of coverage, distance, and connectivity of the both infrastructures. When covariates are controlled, a higher index of material deprivation is associated with (i) a lower presence of, greater distance to, and lower coverage of bike-sharing docking stations; and (ii) is not associated with the presence of, distance to, connectivity of, and coverage of cycle lane networks. Based on these findings, efforts should be directed to increase access to bike lanes and bike-sharing systems to more deprived areas.

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Bike lane; bike sharing; cycling infrastructure; disparities; equity

Introduction

Cycling is now widely recognised as a means of responding to the dual challenges of public health and environmental sustainability (Morabia and Costanza 2010). Many studies have linked daily bicycle use to increased physical activity (Pucher *et al.* 2010, Pan *et al.* 2021) as well as to a consequential reduction in co-morbidities such as obesity (Brown *et al.* 2016), cardiovascular diseases (Boone-Heinonen *et al.* 2009, Alessio *et al.* 2021), and psychological stress (Lorenz 2018, Synek and Koenigstorfer 2019, Ma *et al.* 2021). These benefits seem to outweigh the risks associated with the use of a bicycle (De Hartog *et al.* 2010, Tainio *et al.* 2016, Mueller *et al.* 2018). The use of bicycles is also seen as a means of reducing air pollution (Johansson *et al.* 2017), greenhouse gas emissions (Zhang and Mi 2018, Bucher *et al.* 2019, McQueen *et al.* 2020), and energy dependence (Zhang and Mi 2018, Bucher *et al.* 2019). Furthermore, expanding bike infrastructures reduces the direct exposure of cyclists to automobile traffic through flows separation, thus reducing the risk of accidents and exposure to pollutants emitted by motor vehicles (Monsere *et al.* 2012, Parker *et al.* 2013, Kondo *et al.* 2018). The sense of safety offered by bike lanes – particularly segregated ones – is frequently considered a way to promote bicycle usage and modal shifts from the private car to soft modes (Hull and O'Holleran 2014, Hong *et al.* 2020), and in some cases it has contributed to increases in bicycling trips (Dill and Carr 2003, Wardman *et al.* 2007, Xing *et al.* 2010, Buehler and Dill 2016).

Based on these advantages, for several years a growing number of cities have extended their cycling network to include on-street and off-street cycle lanes and the construction of specific infrastructures to ensure the continuity of networks (Pucher *et al.* 2010, Midgley 2011, Buehler and Pucher 2012, Bauman *et al.* 2017, Hirsch *et al.* 2017, Eren and Uz 2020). In the 1990s, after pioneering cities such as Copenhagen and Amsterdam had developed their first cycling infrastructures in the 1960s and 1970s (Wardlaw 2014, Carstensen *et al.* 2015), cities in high-income countries followed suit and invested significantly in cycling infrastructure. During this bicycle revival (Pucher *et al.* 2010), many cities expanded their networks and registered large percentages of new cyclists. Paris, for instance, registered a 154% increase in the number of cyclists on six major streets between 1997 and 2008 (Pucher *et al.* 2012). By the end of the 1990s, Latin American and Asian cities followed the trend with increasing success in terms of modal shares, as demonstrated by the example of Bogotá, where the cycling

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mode share rose from 0.4% to 5% between 1999 to 2008 in what has become South America's largest bicycle network (Parra *et al.* 2018, Tucker and Manaugh 2018).

The rise of bike sharing systems has also resulted from a long process dating back to the 1960s and initially restricted to experiments in a few European cities (Midgley 2011, Bauman *et al.* 2017, Eren and Uz 2020). From the 1990s on, new technological advances such as smartphones, automated smartcards, and GPS tracking methods have allowed bike sharing programs to spread around the world. With the acceleration of climate urgency, bike-sharing systems have become a major component of sustainable mobility strategies in the last few years as well as one of the main symbols of urban sustainability. Recent accounts suggest the existence of more than 3,000 bike-sharing systems around the globe in 2021 (Yu *et al.* 2021), compared to approximately 800 in 2015 (Bauman *et al.* 2017). With the COVID-19 pandemic, many cities have recently intensified their investment in cycling infrastructures (Hong *et al.* 2020, Fischer and Winters 2021, Musselwhite *et al.* 2021, Nikitas *et al.* 2021).

However, questions have been raised about equitable access to infrastructure and the use of bicycles, as observers argue that disadvantaged groups have lower access to bike sharing systems and bike lanes than high-income population (Morabia and Costanza 2012, Lubitow *et al.* 2019, Doran *et al.* 2021). This study thus examines whether an area-level material deprivation index is associated with differences in access to Lisbon's cycling network and bike-sharing docks network. We hypothesise that the most deprived neighbourhoods tend to have worse access to the cycling network. This approach offers additional evidence that can provide public authorities with recommendations for future cycling network extension projects.

The role of cycling infrastructures in social equity

As a resource, a means of access, and a producer of externalities, the provision of transport always raises questions of distributive fairness. The allocation of public investments can either strengthen or reduce socio-spatial discrepancies in economic opportunities and quality of life as well as health and well-being (Fainstein 2009). Cycling investments impact costs and benefits for different users. An unequitable distribution of cycling access may pose a real problem if it results in sociodemographic differences in uses, practices and exposure to the negative externalities of other infrastructures, with possible health consequences.

Access to cycling infrastructure tends to positively influence their actual use (Shaheen *et al.* 2014, Yu *et al.* 2018), especially in the case of more vulnerable communities (Ogilvie and Goodman 2012, Goodman and Cheshire 2014, Yu *et al.* 2018, Wang and Lindsey 2019, Qian and Jaller 2020). Access to a bike-sharing system (BSS) enables people to avoid the various direct costs associated with owning a bicycle, such as maintenance costs, risk of theft, occupancy of space in the home (McNeil *et al.* 2017, Duran *et al.* 2018). Because access to a cycling network allows cyclists to ride at least in part in segregated paths, it may also reduce costs associated with insecurity (Thomas and DeRobertis 2013). People who do not have a bicycle lane close to home are at greater risk than those who can easily access one, with the inevitable result being that they are less likely to use bicycles when commuting. People with lower access to cycling infrastructures may be deprived of opportunities for physical activity that would contribute to the reduction of certain risk factors linked to obesity and cardiovascular diseases – which already particularly affect such groups (Doom *et al.* 2017, Assari 2018, Bell *et al.* 2018). They also lose access to an inexpensive mode of daily travel, which may reinforce a possible situation of forced car ownership in the absence of an alternative mode of transportation (Curl *et al.* 2018, Currie *et al.* 2018). Imbalances in the supply of transport infrastructure translate into unequal levels of access to resources and opportunities (Hernandez 2018). In addition, the construction of cycle lanes is often accompanied with other local measures of urban design aimed at improving the quality of public space. People living in areas that do not benefit from these improvements continue to be exposed to road traffic, noise, air, and visual pollution.

In concert with the growing investments being made in varying contexts, studies of cycling infrastructure distribution have increased during the last decade. Researchers have generally observed that certain social categories are frequently under-represented among cyclists, including women, ethnic minorities, and low-income groups (Ogilvie and Goodman 2012, Goodman and Cheshire 2014, Nickkar *et al.* 2019, Wang and Lindsey 2019). Concerns about traffic safety and personal safety – for example due to racial and gender discrimination experienced while riding – are among the main barriers mentioned by respondents (McNeil *et al.* 2017, Lubitow *et al.* 2019). These discrepancies may reflect the existence of a more prevalent demand within a more affluent population that is more sensitive to the sustainable mobility paradigm and has the capacity to intervene in the political sphere (Golub *et al.* 2016) and demand a better living environment. Infrastructure supply would thus be related to demand, which generally rises more significantly where a larger proportion of young adults live and where cycling modal shares are higher (Winters *et al.* 2010, Flanagan *et al.* 2016). These same populations are also more present than low-income groups and minorities in participating in planning processes and in voicing demands at the local level (Golub *et al.*

2016). Bicycle lanes and bike-sharing services are one element among others that contribute to the attractiveness of urban areas for young creative classes and wealthier citizens (Hoffmann 2013, Lubitow *et al.* 2019). Concentrating investment efforts on affluent, central neighborhoods could limit access to cycling infrastructure for those who have a greater need for such transport in the absence of alternative ways to travel.

Overall, current evidence increasingly supports the notion that spatial discrepancies in cycling infrastructures may negatively impact those populations that may be most in need of them for their daily mobility (Allen and Farber 2019). However, several researchers have emphasized the relative paucity of existing studies and the need to continue analyses in different contexts (Braun *et al.* 2019, Chen and Li 2021, Firth *et al.* 2021). The vast majority of existing studies were undertaken in the United States and Canada, along with a few studies conducted in South American cities where massive socio-spatial inequalities have increasingly triggered a search for solutions. Surprisingly, Europe and Asia are under-represented in this literature; in particular, to the best of our knowledge, no studies have been conducted in Southern Europe to date.

Materials and methods

Study area

Over the past decade, the city of Lisbon (100 km^2, 508,000 inhabitants in 2019 – Statistics Portugal data) has developed a number of measures to promote bicycle use. Since 2008, the construction of cycle lanes has grown intensely in the city, reaching a total of 175 km of cycle lanes in 2022 (of which 152 km are visually or physically segregated lanes) out of a total of 1,662 km of road network (Figure 1). The expansion process has not been without difficulties, with multiple opponents arguing that the Lisbon street network is not suited to the use of bicycles and that the city is too hilly to accommodate cycling (Figure 2). The former Mayor of Lisbon intended to reach 200 km by the end of 2021,[1] but this plan may undergo modifications because a new mayor with less clear intentions regarding cycle lanes policy was elected in September 2021. In 2017, the Gira BSS was established, with the gradual opening of 131 bike-sharing docks (in April 2022) and the provision of more than 1,000 bicycles (Félix *et al.* 2020). Coupled with other measures (*e.g.*, campaigns to promote bicycle use, free passes during the initial phase of the system), these policies have resulted in a sharp increase in bicycle use. For example, Félix *et al.* (2020) noted a 3.5-fold increase in cyclists after the expansion of the cycling network. Nevertheless, bicycle use remains dependent on the improvement of the conditions offered by the cycle infrastructures (Moura *et al.* 2017, Félix *et al.* 2019).

Data sources

This study relied on three main data sources that were grouped together using ArcGis Pro 2.9.2 to build the variables. The 2011 Census data – the most recent with

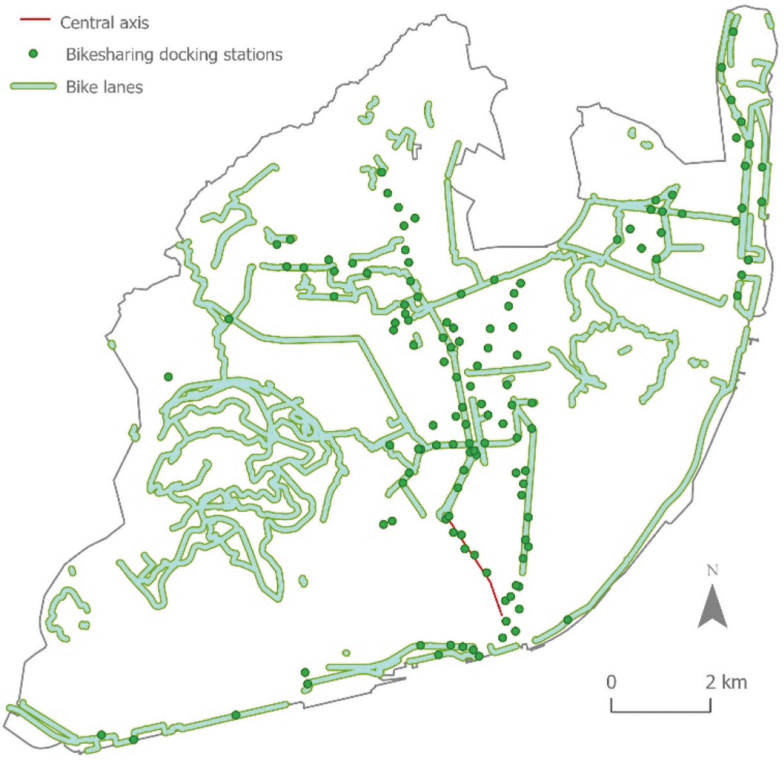

Figure 1. Cycling infrastructures. Source: Lisbon City Council open data.

Figure 2. Average slopes. Source: Lisbon City Council open data.

data at the local level available in Portugal[2]—provided population data at the block group level (*secções estatísticas* in Portuguese). Block groups are geographical areas of variable size depending on the built environment and the location. In Lisbon, the 1,061 block groups included in this study[3] are 7.78 hectares on average (SD = 15.8 hectares) and include 308 dwellings (SD = 83) and 520 residents (SD = 186). The spatial data of slopes, cycle lanes, and the list of stations in the Gira bike-sharing system are made available by the City of Lisbon as part of the open data policy. The road network was provided by ArcGIS Pro 2.9.2 through its 'Network Analyst' tool. The cycle network data includes several types of cycle lanes, among which are off-street bike lanes, off-street multi-use trails and paths, on-street bike lanes, and on-street, non-segregated bike lanes. Bike lane and BSS data were obtained in April 2022.[4]

Dependent variables

The cycle network and the bike-sharing docking stations network that were analysed correspond to the situation of the network in April 2022 according to public data available. Regarding the cycle network, visually or physically non-segregated lanes were removed from the sample, as they do not allow for any separation (neither physical nor visual) between cyclists and automobile traffic. These sections represent 23.5 km (13.4% of the total), leaving the remaining 151.5 km included for analysis.

Several dependent variables, largely inspired by the work of Houde *et al.* (2018) and Braun *et al.* (2019), were created to characterise accessibility in cycle mode (Table 1, Figure 4); four dependent variables relate to the cycle network, and three are for bike-sharing docking stations. These variables are based on a network-based measure of the distances from the centroids of the block groups. The precise location of block group centroids is weighted by the population of census blocks – the most local level of statistical information available – included in block groups. The variables are as follows:

(i) Bike lane (BL) presence: a binary measure of the presence of a bike lane, indicating whether a bike lane was at a 5-min walk from the block group centroid (value 1 if yes, 0 otherwise). The choice of the distance threshold was based on a commonly accepted 1.4 m/s walking speed (Fitzpatrick *et al.* 2006);
(ii) BL distance: a continuous measure of the distance to the nearest bike lane from the block group centroid;
(iii) BL coverage: a continuous measure of bike lane length per km of the street network in a 500 m network-based radius from the block group centroid;
(iv) BL connectivity: a continuous measure of the distance that can be travelled from a block group in any direction without encountering a break in the bike lane network of more than

Table 1. Description of variables.

Categories	Variables	Description and measurement
BIKE	BL presence	Binary indicator of bike lane presence at a 5-min walk from block group centroid[b, c]
	BL coverage	Bike lane length per km of streets, in a network-based 500 m radius from block group centroid[b, c]
	BL connectivity	Distance that can be travelled from a block group in any direction without encountering a break more than 150 m in the bike lane network – providing that there is a bike lane at a 5-min walking distance[b]
	BL distance	Distance to the nearest bike lane[b]
	BSS presence	Binary indicator of the presence of a bike-sharing docking station at a 5-min walk from block group centroid[b]
	BSS coverage	Number of bike-sharing docking stations per km of street network, in a 500 m network-based radius from block group centroid[b, d]
	BSS distance	Distance to the nearest bike-sharing docking station[b]
MDI	MDI	Material deprivation index: mean of 4 z-scores (% of households living in rented houses; % of unemployed among the active population; % of people with elementary education; average number of occupants per room)[a]
COV	Population density	Number of residents per km^{2}[a]
	Distance to central axis	Network-based distance between block groups centroids and a line joining four central points (Saldanha, Marquês de Pombal, Restauradores, Baixa-Chiado) [c]
	Young adults	% of residents aged 18-35[a]
	Average slope	Average slope of the streets located in a network-based 500 m radius around block group centroids[b, c]

Sources: [a] Statistics Portugal—2011 Population Census; [b] Lisbon City Council open data (slopes, bike lanes, and bike-sharing docking stations): https://geodados-cml.hub.arcgis.com/and https://www.gira-bicicletasdelisboa.pt/descobre-as-estacoes/; [c] ArcGIS Pro 2.9.2 StreetMap using Network Analyst tool (ESRI, Redlands, CA).

150 m – providing that there is a bike lane at a 5-min walk from the block group centroid. A break of 150 m was accepted as it may represent the distance between two opposite sides of a major crossroads. A careful inspection of the 120-300 m discontinuities existing in the Lisbon cycling network confirmed that this threshold is sensible in terms of cycling practice;

(v) Bike-sharing docking station (BSS) presence: a binary measure of the presence of a bike-sharing docking station at a 5-min walk from the block group centroid;

(vi) BSS distance: a continuous measure of the distance to the nearest bike-sharing docking station from the block group centroid;

(vii) BSS coverage: a continuous measure of the number of bike-sharing docking stations per km of street network, in a 500 m network-based radius from the block group centroid.

Independent variables and covariates

Area-level social vulnerability was measured through a material deprivation index (MDI). Census data was used to calculate the MDI for each block group (Figure 3and Table 1). This index draws on four census data variables: home ownership (percentage of households living in rented houses), unemployment rate (percentage of unemployed among the active population), low educational level (percentage of people with a degree lower or equal to middle school diploma), and household overcrowding (average number of occupants per room). All four indicators were standardised to the Lisbon means and then summed to form the MDI. This approach is similar to the z-score-based Carstairs and Morris' method (Carstairs and Morris 1990, Norman and Darlington-Pollock 2017, Norman *et al.* 2019), and the choice of indicators was based on Landi *et al.* (2018). This kind of measures has been utilised in health studies that have assessed unhealthy behaviour and obesity (Santana *et al.* 2009); diabetes mellitus-related mortality, infectious and parasitic diseases, chronic liver disease, diabetes, and ischemic heart disease (Santana Costa *et al.* 2015); mental health (Loureiro *et al.* 2019); suicide (Santana Costa *et al.* 2015); and limited access to emergency hospital services (Silva and Padeiro 2020).

Other covariates (Table 1) include population density (persons/km^{2}); the distance to a central axis formed by four points (Saldanha, Marquês de Pombal, Restauradores, and Baixa-Chiado metro stations) as a proxy for distance to the major services and employment centre; the percentage of residents between the ages of 18 and 35, an age group for which the percentage of cyclists is generally higher; and the average slope of streets within a network-based radius of 500 m from the block group centroid, as slopes are potentially a major constraint in cycling infrastructure development (Figure 2).

Method

Alongside the descriptive statistics, independent *t*-tests were used to compare the material deprivation index of block groups with a cycle lane and/or a bike-sharing docking station at a 5-min walking distance with that of block groups without a cycle lane and/or a bike-sharing docking station. The tests were extended to other variables (coverage, connectivity, and distance). Regarding the distance-based variables, the block groups were divided into two categories based on the median of the indicator. Finally, an ordinary least squares (OLS) regression model was performed to estimate the associations of the multiple deprivation index with each dependent bike lane and bike-sharing docking station variable, adjusting for covariates. The model takes the following form:

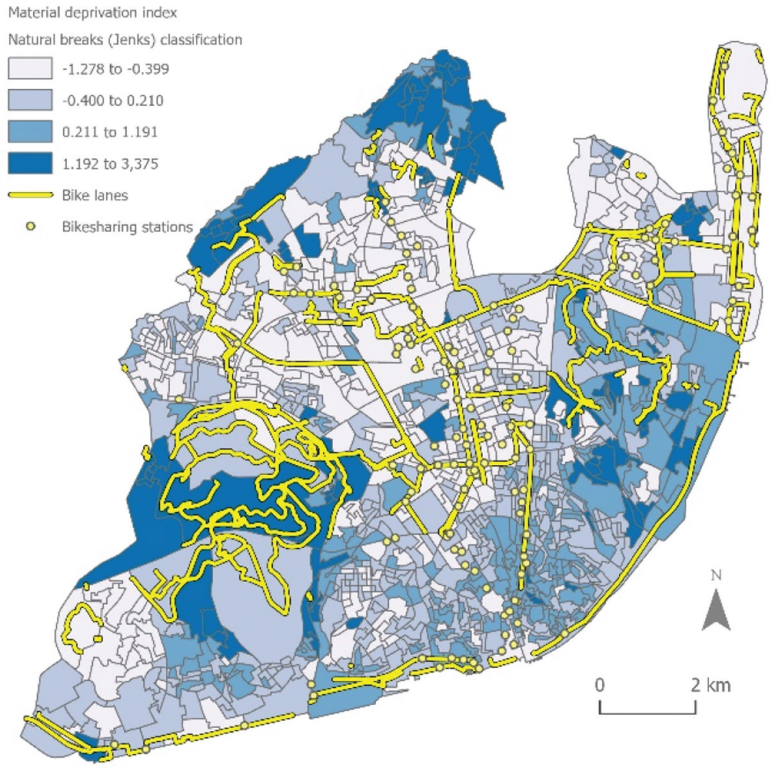

Figure 3. Material deprivation index. Sources: Statistics Portugal—2011 population census; Lisbon City Council open data.

$$\mathrm{BIKE_i} = \alpha + \beta_1\, \mathrm{MDI_i} + \beta_2\, \mathrm{COV_i} + \varepsilon_i$$

where $\mathrm{BIKE_i}$ represents the vector for all the dependent variables tested, α is the constant of the equation, β_1 and β_2 are the parameters of vectors MDI (multiple deprivation index) and COV (covariates), and ε_i is the error term. Table 1 provides a detailed account of the variables tested in each vector. For the two binary variables (presence of a bike lane, presence of a bike-sharing docking station), a logistic regression model was preferred to estimate the likelihood of having a bike lane or a bike-sharing docking station at a 5-min walk.

Results

Descriptive and bivariate analyses

Table 2 provides the descriptive statistics for the different variables, and Table 3 provides the pairwise correlations between variables. About 43% of the block groups have a cycle lane within a 5-min walk. Among these, the average distance to the nearest cycle lane is 242 m (SD = 112.7), the average coverage is 0.11 km of bike lanes per km of street network (SD = 0.07), and the total length of directly accessible cycle lanes without deviating significantly from the network is 72.3 km (SD = 49.6). These block groups are on average 701 m from the nearest bike-sharing station (SD = 622.9). The average distance to the nearest bike lane is 777 m for other block groups (SD = 270.5), and the average distance to the nearest bike-sharing docking station is 1.1 km (SD = 0.6).

Only 27% of the 1,061 block groups have a bike-sharing docking station within a 5-min walk. The average distance to the nearest cycle lane is 313 m (SD = 223.9; compared to 637 m for block groups without a bike-sharing docking station nearby, SD = 337.8), the average coverage is 0.09 km of bike lanes per km of street network (SD = 0.09), and cyclists also have 61.8 km of directly accessible cycle lanes (SD = 53.0). These block groups are on average 269 m from a docking station (SD = 101.0) and have an average of 0.29 docking stations per km of road (SD = 0.14).

Independent *t*-tests compared block groups with a cycle lane and/or bike-sharing docking station with those without such amenities in terms of material deprivation index (Table 4). As said earlier, a higher MDI means a more vulnerable population while a lower MDI indicates a less vulnerable population. On average, block groups with a bike lane at a 5-min walk have a lower MDI ($M = > -0.062$, $SE = 0.039$) than block groups without bike lanes ($M = 0.047$, $SE = 0.030$), $t(907.72) = 2.2198$, $p = 0.027$. Regarding access to bike-sharing docking stations, on average, block groups with a bike-sharing docking station at a 5-min walk have a lower MDI ($M = -0.277$, $SE = 0.032$) than block groups without a station ($M = 0.105$, $SE = 0.030$), $t(785.97) = 8.710$, $p < .01$. Most of the other indicators constructed for the analysis also show significant

Figure 4. BL/BSS connectivity and coverage. Sources: Statistics Portugal—2011 population census, Lisbon City Council open data, ArcGIS Pro 2.9.2 StreetMap using network analyst tool (ESRI, Redlands, CA).

Table 2. Descriptive statistics and measurement of variables.

	All block groups		Presence of bike lanes at a 5-min walk				Presence of bike-sharing docking stations at a 5-min walk			
	(n = 1,061)		No lanes (n = 608)		Any lanes (n = 453)		No docking station (n = 771)		Any docking station (n = 290)	
Variables	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BL presence	0.43	0.49	0	0	1	0	0.31	0.46	0.75	0.43
BL coverage	0.05	0.09	0.01	0.06	0.11	0.08	0.03	0.08	0.09	0.09
BL connectivity	30,864.20	48,249.81	0	0	72,288.99	49,582.16	19,245.35	40,684.40	61,754.31	53,019.76
BL distance	548.63	342.69	777.06	270.54	242.04	112.74	637.23	337.77	313.07	223.93
BSS presence	0.27	0.45	0.12	0.33	0.48	0.50	0	0	1	0
BSS coverage	0.09	0.15	0.04	0.11	0.15	0.17	0.01	0.04	0.29	0.14
BSS distance	930.17	650.13	1,100.70	617.21	701.30	622.92	1,178.99	592.66	268.68	101.05
MDI	0.00	0.78	0.07	0.66	−0.04	0.83	0.07	0.81	−0.24	0.61
Pop. density	15,562.95	10,958.41	17,078.90	10,285.19	14,810.33	11,208.79	16,201.89	11,328.82	13,341.52	9,242.62
Distance centre	3,645.02	2,369.94	3,470.75	2,450.27	3,731.54	2,325.94	4,010.57	2,244.57	2,374.10	2,359.94
% 18-35	23.26	6.01	23.15	5.04	23.32	6.44	23.01	5.14	24.14	8.31
Slope	4.27	1.94	4.70	1.85	3.69	1.91	4.57	1.82	3.46	2.01

Table 3. Pairwise correlations between variables at the block group-level (n = 1,061 block groups).

	BL presence	BL distance	BL connectivity	BL coverage	BSS presence	BSS distance	BSS coverage	MDI	% 18-35	Pop. density	Distance centre	Slope
BL presence	1.000											
BL distance	−0.773***	1.000										
BL connectivity	0.741***	−0.575***	1.000									
BL coverage	0.577***	−0.579***	0.519***	1.000								
BSS presence	0.398***	−0.422***	0.393***	0.334***	1.000							
BSS distance	−0.304***	0.403***	−0.347***	−0.214***	−0.624***	1.000						
BSS coverage	0.358***	−0.386***	0.420***	0.391***	0.836***	−0.580***	1.000					
MDI	−0.069**	0.141***	−0.144***	−0.069**	−0.218***	0.379***	−0.211***	1.000				
% 18-35	0.014	−0.020	−0.008	0.016	0.044	−0.063**	0.046	0.125***	1.000			
Pop. density	−0.087***	0.118***	−0.056*	−0.133***	−0.072**	−0.012	−0.077**	0.105***	0.061**	1.000		
Distance centre	−0.014	0.046	−0.099***	0.085***	−0.233***	0.389***	−0.176***	0.033	−0.070**	−0.094***	1.000	
Slope	−0.256***	0.285***	−0.247***	−0.301***	−0.256***	0.106***	−0.270***	0.298***	0.126***	0.124***	−0.419***	1.000

***p < .001; **p < .01; *p < .05.

Table 4. Independent *t*-tests results (applied to MDI).

Variables	Description of groups of lower and higher values	Lower values in access indicators		Higher values in access indicators		
		M	SE	M	SE	*t*-test
BL presence	0 (no presence) vs. 1 (presence)	0.047	0.030	−0.062	0.039	2.2198**
BL distance[a]	Below median distance vs. equal/over median distance	−0.178	0.050	0.053	0.059	2.986***
BL distance	Below median distance vs. equal/over median distance (all block groups)	−0.051	0.036	0.052	0.031	2.166**
BL connectivity[a]	Below 20 km vs. equal/over 20 km	0.175	0.077	−0.184	0.042	−4.105***
BL coverage[a]	Below median coverage vs. equal/over median coverage	0.014	0.055	−0.138	0.055	−1.947*
BSS presence	0 (no presence) vs. 1 (presence)	0.105	0.030	−0.277	0.032	8.710***
BSS distance[b]	Below median distance vs. equal/over median distance	−0.341	0.042	−0.212	0.048	2.035**
BSS distance	Below median distance vs. equal/over median distance (all block groups)	−0.191	0.025	0.191	0.039	8.221***
BSS coverage[b]	Below median coverage vs. equal/over median coverage	−0.290	0.046	−0.263	0.044	0.422

***p < .001; **p < .01; *p < .05.

[a] only for those with a bike lane at a 5-min walk.

[b] only for those with a Gira bike-sharing docking station at a 5-min walk.

differences (Table 4). For example, the average value of the MDI of block groups with access to more than 20 km of cycle lanes without major discontinuities is −0.184 (SE = 0.042), against 0.175 (SE = 0.077) for those without access, *t*(248.57) = −4.105, *p* < .01. The indicators are systematically favourable to the least vulnerable block groups, with the exception of the distance to the nearest bike lane, for which the *t*-test is non-significant.

Regression analysis

Before proceeding to the statistical analyses, assumptions were checked, which revealed no multicollinearity issues (variable inflation factor values were always < 2). Linearity and homoscedasticity were tested using plots "observed versus predicted" and "residuals versus predicted values". Evidence of spatial autocorrelation in the data was found using the Durbin-Watson test. However, as stated by Braun *et al.* (2019), levels of accessibility to cycling infrastructures are inherently clustered in space, which means that autocorrelation may not be accounted for in the models to avoid over-adjusted models (Braun *et al.* 2019). This study thus follows their recommendation of not taking autocorrelation into account. Since the objective of the study is to identify associations rather than causal relationships, this approach, also followed by Houde *et al.* (2018), is acceptable.

The results of the linear and logistic regression models are provided in Tables 5 and 6. Overall, the results regarding bike-sharing docking stations are more expressive than those concerning bicycle lanes. Models 6 and 7 show higher adjusted R^2 than models 2 to 4, while model 5 shows higher χ^2 and Nagelkerke R^2 than model 1. This contrast might be due to the fact that the Lisbon bike-sharing system is currently less developed than the bicycle lane network and is therefore more geographically (and socially) selective, while bike lanes are becoming more pervasive across the city and are less suited to statistical explanation through our variables.

As the co-variates are controlled for in the models, the material deprivation index now offers more mixed results, as the statistical association of the MDI with bike lane indicators (presence, distance, connectivity, and coverage) is non-significant. However, lower scores (describing a lower level of social vulnerability) are associated with higher docking stations coverage (β = −0.089, p = 0.003) and with more reduced distance to bike-sharing docking stations (β = 0.312, p < .001). Block groups with higher social vulnerability (high MDI) are also at a disadvantage in terms of the presence of a bike-sharing docking station within a 5-min walk (OR = 0.597 , p < 0.001).

The share of the population aged 18-35 is not associated with the presence of bike lanes nor with bike lane connectivity, but it is associated with every other indicator. A higher proportion of this age group is associated with a shorter distance to the nearest bike lane (β =−0.060, p = 0.040) and with greater bike lane coverage (β = 0.056, p = 0.059). The proportion of people aged 18-35 is also linked to the presence of a docking station (OR = 1.039 , p = 0.004), a reduced distance to the nearest docking station (β = −0.096, p < 0.001), and greater bike-sharing stations coverage (β = 0.086, p = 0.002).

The other three covariates (population density, distance from the central axis, average slope) are generally associated with the indicators. In the case of population density, the direction of the coefficients indicates an unfavorable relationship: a higher population density is statistically associated with a greater distance from the cycling network (β = 0.094, p = 0.001), lower bike lane coverage (β =−0.104, p < .001), and lower docking stations coverage (β = −0.057, p = 0.043). No significant relationship with bike lane presence and connectivity was found, and the same applies to the presence of and distance to bike-sharing docking stations. Meanwhile, the distance from the central axis is not associated with the presence of a bike lane, but it is associated with almost all the other indicators: bike lane distance (β = 0.199, p < 0.001), connectivity (β = −0.240, p < 0.001), and coverage (β = −0.061, p < 0.001); and bike-sharing

Table 5. Regression results (bike lanes).

	Model 1: BL presence				Model 2: BL distance		Model 3: BL connectivity		Model 4: BL coverage	
			95% CI							
Variables	B (SE)	OR	Lower	Upper	β coef	*p*-value	β coef	*p*-value	β coef	*p*-value
intercept	1.673 (0.379)									
mdi	0.107 (0.089)	1.113	−0.069	0.282	0.026	0.402	−0.037	0.234	0.036	0.246
% pop 18-35	0.017	1.017	0.005	0.040	−0.060	0.040*	0.041	0.164	0.056	0.059*
population density	−0.000**	1.000	0.000	0.000	0.094	0.001**	−0.036	0.225	−0.104	<0.001***
distance centre	−0.000***	1.000	0.000	0.000	0.199	<0.001***	−0.240	<0.001***	−0.061	0.006*
average slope	−0.388***	0.678	−0.476	−0.303	0.356	<0.001***	−0.337	<0.001***	−0.332	<0.001***
Observations	1,061				1,061		1,061		1,061	
−2LL	1,346.18				-		-		-	
Nagelkerke R^2	0.123				-		-		-	
χ^2	101.957				-		-		-	
AIC	1,358.2				-		-		-	
Adj. R^2	-				0.122***		0.111***		0.103***	
F(5, 1055)	-				30.55		27.35		25.31	

Table 6. Regression results (bike-sharing docking stations).

	Model 5: BSS presence				Model 6: BSS distance		Model 7: BSS coverage	
			95% CI					
Variables	*B (SE)*	OR	Lower	Upper	β coef	*p*-value	β coef	*p*-value
intercept	2.259 (0.452)							
mdi	−0.515 (0.142)***	0.597	−0.804	−0.245	0.312	<0.001***	−0.089	0.003***
% pop 18-35	0.039 (0.013)***	1.039	0.013	0.066	−0.096	<0.001***	0.086	0.002***
population density	−0.000 (0.000)*	1.000	0.000	0.000	−0.023	0.373	−0.057	0.043**
distance centre	−0.001 (0.000)***	1.000	−0.001	0.000	0.463	<0.001***	−0.335	<0.001***
average slope	−0.591 (0.059)***	0.554	−0.710	−0.477	0.222	<0.001***	−0.388	<0.001***
Observations		1,061			1,061		1,061	
−2LL		974.772			-		-	
Nagelkerke R^2		0.325			-		-	
χ^2		269.866			-		-	
AIC		986.77			-		-	
Adj. R^2		-			0.324***		0.187***	
F(5, 1055)		-			102.8		49.74	

docking stations distance ($\beta = 0.463$, $p < 0.001$) and coverage ($\beta = -0.335$, $p < 0.001$). The average slope follows the same trend. A higher slope is associated with worse indicators of access to bicycle lanes: presence (OR = −0.388, $p < 0.001$), distance ($\beta = 0.356$, $p < 0.001$), connectivity ($\beta = -0.337$, $p < 0.001$), and coverage ($\beta = -0.332$, $p < 0.001$). Higher slopes are also associated with the presence of a bike-sharing docking station (OR = −0.591, $p < 0.001$), the distance from the nearest docking station ($\beta = 0.222$, $p < 0.001$), and bike-sharing system coverage ($\beta = -0.388$, $p < 0.001$).

Discussion

The purpose of this study was to examine whether the area-level material deprivation index is associated to differences in access to the bicycle network and the bike-sharing docking network in Lisbon. We hypothesised that the most deprived neighborhoods tend to have poorer access to the cycling network and to bike-sharing docking stations. To test this hypothesis, independent *t*-tests and regression models were performed. The results of independent *t*-tests confirm the hypothesis that a significant difference exists between the most and least deprived block groups in terms of the presence of bike lanes and bike-sharing docking stations as well as the coverage, distance, and connectivity of related infrastructures. The difference is systematically favorable to less deprived areas. Furthermore, when controlling covariates, the analyses indicate that a higher material deprivation index is associated with (i) a lower presence of, greater distance to, and lower coverage of bike-sharing docking stations; however, it is not associated with (ii) the presence of, distance to, connectivity of, and coverage of cycle lane networks. It is important to recall here that, regardless of the importance of dependent variables, the resulting situation as measured through *t*-tests reflects differences between groups. The non-significance of the MDI when controlling other variables does not mean that there is no difference between areas with high MDI and areas with low MDI.

These results thus support the claims of those who fear the existence of inequalities in access to the use of bicycles (Morabia and Costanza 2012, Lubitow *et al.* 2019, Doran *et al.* 2021). They are consistent with empirical observations of other authors (Teunissen *et al.* 2015, Tucker and Manaugh 2018, Braun *et al.* 2019, Firth *et al.* 2021, Mora *et al.* 2021). For example, in Santiago de Chile, most bike lanes are concentrated in central areas where the middle- and upper-middle income groups live (Mora *et al.* 2021). Another study based on five Brazilian cities showed that bike-sharing systems had an unequal social and spatial distribution and that they generally favour better-off areas (Duran *et al.* 2018). In Bogotá, Colombia, Parra *et al.* (2018) highlighted that the differences in access are unfavourable to lower-income groups. Based on the case of 22 U.S. cities, Braun *et al.* (2019) have also shown that certain areas (with lower educational attainment, a higher proportion of Hispanic residents, and lower composite socio-economic status) had less access to the cycling network. However, the authors did not detect inequalities in access for other characteristics (higher proportions of Black residents, lower income, higher poverty). Furthermore, individuals in London using the bike-sharing system were more likely to live in areas of low deprivation (Ogilvie and Goodman 2012).

Our findings suggest that funds devoted to the expansion of the cycling and bike-sharing network may have not contributed to reduce current inequalities in access to active mobility, and could even reinforce them. As the variables of population density and average slopes show, access disparities are partly linked to the underlying socio-spatial inequalities embedded in the territorial and physical structure of the city. The cycling and bike-sharing networks tend to avoid hillier and densely-populated neighbourhoods, where many low-income residents live. As recognised by Braun *et al.* (2019), discriminatory practices may not be at play and the spatial distribution of the network may be the result of a broader set of factors. It is even possible that the future expansions reduce the current discrepancies. Since this network may be expanded in the future, it is possible to envisage that the network will become more accessible to low-income groups. It will be crucial to monitor the progression of the cycling infrastructures and its impacts. Houde *et al.* (2018) observed, for instance, that the expanding network in Montreal allowed low-income groups, migrants, and seniors to gain access to the cycling network.

In the immediate term, several reasons may be invoked to explain these disparities. The first reason may be linked to the fears of public authorities. The most deprived neighbourhoods generally have few amenities and have a higher unemployment rate, which may cause lower levels of bicycle utilisation and reduce the financial sustainability of the project. Although low-income neighbourhoods tend to use bicycles less (Kretman Stewart *et al.* 2013, Caspi and Noland 2019), in several contexts, supporting infrastructure through specific campaigns and paying attention to affordability has ensured increased use by low-income groups (Kretman Stewart *et al.* 2013, Parker *et al.* 2013, Goodman and Cheshire 2014).

A second possible reason lies in the predominance of an approach to the planning of infrastructure that is more technical and linked to costs, and less social and linked to the need to rebalance the means of mobility between various social groups. In this approach, bike lanes are predominantly directed to locations where their construction and urban insertion is technically easier or less expensive. In Lisbon, the avoidance of steep, narrow streets in the historic centre may be part of this rationale. This idea joins the argument of Braun *et al.* (2019) that equity issues are not fully integrated into the policy that guides infrastructure investments. The segmentation of the different departments in city councils makes it difficult to articulate them and integrate the different issues. An analysis of the documents issued by the city of Lisbon shows that most of the arguments mobilised for the development of cycle lanes concern the local quality of life through urban design and the improvement of air quality (CML 2018). Social equity considerations are absent from these documents. Furthermore, no social indicator is mentioned in the documents. This absence has also been identified in the case of Bogotá (Parra *et al.* 2018), and the subject of socio-spatial equity should be better integrated in network extension projects. Disadvantaged groups may face additional health and social issues due to their exclusion from infrastructures that can act as a leverage to stimulate active mobility and physical activity (Sallis *et al.* 2013, Noyes *et al.* 2014). Understanding the underlying reasons for this choice of development would require a thorough analysis of the advocacy and institutional motivations.

A third possible reason is related to the aforementioned existence of a more prevalent demand within a younger and more affluent population. The results of the models confirm this assumption and are consistent with other studies (Winters *et al.* 2010, Flanagan *et al.* 2016).

Finally, cycle infrastructures enhance the visual quality and local character of neighbourhoods, and they serve as a symbol of liveability and sustainability; in other words, they promote the image of the city (Ibsen and Olesen 2018). Building cycling infrastructure in centrally located areas may also be considered a tool for strengthening public interventions in the public space linked to urban regeneration (Stein 2011, Hoffmann 2013). As embedded in the broader context of financialization, gentrification, and touristification, cycling investments can thus reinforce local exclusionary dynamics (Ibsen and Olesen 2018), and there may be grounds for fearing that expanding cycling networks to low-income areas may trigger gentrification processes (Stehlin 2015, Flanagan *et al.* 2016). This possibility needs greater attention and needs to be monitored by public authorities. It is also a significant topic for future research.

Limitations

This study has several limitations. The first one is that, as a cross-sectional study performing linear and logistic regressions, no causal relationship can be inferred. It should be reiterated that this study sought to identify statistical associations, not causal relationships. Second, this study is based on area-based measures, which may introduce possible homogeneity issues due to the well-known modifiable areal unit problem (Openshow 1979). Moreover, using census block groups also means that every population is assumed to walk from their block centroid, which is not realistic. This method is, however, the most reliable one in the face of available data, and it has been widely used in recent research. A third limitation is that the existence of other infrastructures, services, or policy measures was not taken into account. It is possible that an area which is less served by cycling infrastructure benefits from a good quality public transport network – however, in times of a pandemic, such a network may not be sufficient in light of the heighted risk of contagion. It is also possible that some neighbourhoods have less road traffic and have a lower need for separate cycle lanes. Fourth, the possible effects of other policies and public or private initiatives, such as local area traffic management, dockless bike-sharing or scooters, are not included in this study. Finally, due to the fact that the 2021 population census data will only be available by the end of 2022 (with some uncertainty and a possible additional delay), this study has used data from 2011 while bike-sharing docking stations and bike lanes were assessed in 2022. This disjunction avoids the endogeneity and residential self-selection problem. However, it may also bring the results into question. The last 10 years have been characterized by a strong gentrification and touristification process in Lisbon (Lestegás 2019, Mendes 2021), which has led many vulnerable people to leave the most valued and sought-after areas. The geography of gentrified areas partially overlaps with the geography of bike-sharing docking stations, which raises a question that will deserve attention in the near future: is the recent increase in the number of gentrifiers (or, more generally, of well-off residents) and of (for instance) short-term accommodation statistically associated with the expansion of cycling infrastructures? The direction of the possibly causal relationship will remain difficult to answer. At the same time, it will be important to determine whether non-gentrified, less central, newly served areas have seen their social composition change in the last 10 years more than equivalent areas with no cycling infrastructures.

Conclusion

The results of this study show that the development of the bike-sharing system and the cycling network has so far proceeded unevenly. While the disparities in access and quality of service are partly explained by the physical conditions of the territory, which are also correlated with the distribution of social groups, it is worrying that the development and extension of a system of bike-sharing and cycle lanes do little to lower pre-existing inequities, and instead, they reinforce such problems. The case of Lisbon is paradigmatic of a situation where the planning of the mobility system only partially integrates social considerations. At a time when inequalities in access to resources and opportunities, soft modes, and quality public space translate into inequalities in public health and increased epidemiological and social risks, it becomes crucial that planners and decision-makers take into account socio-spatial disparities in cycling infrastructure development projects.

Notes

1. This intention was regularly disseminated in the Portuguese press since 2016 (https://www.dn.pt/sociedade/lisboa-vai-ter-200-km-para-pedalar-e-quer-ir-de-oeiras-a-vila-franca-5400639.html) and more recently in June 2021 (https://www.jornaldenegocios.pt/economia/detalhe/camara-de-lisboa-anuncia-200-quilometros-de-ciclovia-ate-2021-e-apoios-para-compra-de-bicicletas).
2. The most recent population census was implemented in 2021. However, data at the block group level are expected to be publicly available only by the end of 2022 (https://censos.ine.pt/xportal/xmain?xpgid=censos21&xpid=CENSOS21&xlang=pt).
3. Two block groups with no population were removed from the study.
4. The first version of the paper was based on data gathered in August 2021. For the current version of the paper data have been updated in April 2022.

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