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Accessibility inequality across Europe: a comparison of 15-minute pedestrian accessibility in cities with 100,000 or more inhabitants

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Active accessibility is a paramount objective of current sustainable urban development policies. Recently, the 15-minute city concept emphasized this framework by stressing proximity as a key urban feature. In this paper, we use two accessibility indicators—cumulative opportunities (total destinations) and Variety (number of different types of opportunities)—to evaluate pedestrian accessibility, using a 15-minute threshold, in a sample of European cities with 100,000 or more inhabitants, and measure within-city and between-city inequality, by calculating pseudo-Gini coefficients. Our results show not only that European cities are not 15-minute cities yet, but also that there is significant inequality within them, although less so in cities with high Variety. Our cross-city comparison found diminishing returns between both total destinations and population density and between Variety and density. Our findings suggest that European cities can increase pedestrian accessibility and reduce internal inequality by increasing the Variety of opportunities accessible by foot, along with improvements to pedestrian infrastructure.

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INTRODUCTION

Current analyses of mobility patterns in cities reveal a high level of car dependence, especially in the Western world[1,2]. However, fuelled by health, environmental, and quality of life arguments, cities are trying to reduce car dependence and the associated car modal share. They seek to achieve this by promoting transportation alternatives integrated into a multimodal mobility system, ensuring that opportunities can be accessed using sustainable modes[3]. Active transport modes, i.e., walking and cycling, are paramount in this strategy and are given priority over all other modes, either by allowing direct access to destinations and/or by supporting and increasing access using other sustainable modes, such as public transport and micro-mobility systems. Therefore, *accessibility by active travel modes (henceforth referred to as active accessibility)*, understood as the ability to reach relevant activities, individuals, or opportunities, using active travel[4], has become a key objective in current urban sustainability policies[5,6].

One paramount example of these policies is the 15-minute city concept[7,8], which has recently gained traction in part due to its adoption by the Mayor of Paris as a foundational strategy to structure the city. A key pillar is proximity, which requires relevant destinations to be accessible by foot and/or bicycle in 15 minutes or less, thereby allowing individuals to satisfy their needs and reach relevant opportunities in an acceptable travel time. The concept implicitly stresses the importance of accessing different types of opportunities instead of several opportunities of the same type, reinforcing the importance of activity richness in urban planning[9,10]. However, the concept has three main limitations. First, the relevance of opportunities is hard to determine, as different people might consider different opportunities relevant, originating different daily space-time anchors as Hägerstrand's revealed in the 1970s[11]. Second, the acceptable travel time changes in accordance with the desired destination. Third, walking time is far from being accurately perceived[12], which raises important limitations when setting a predetermined threshold for all individuals and all opportunities.

By stressing access to (relevant) destinations and 15 minutes as an acceptable travel time, it can be translated into a cumulative-opportunities measure of active accessibility. This concept says nothing about which specific opportunities should be considered and, therefore, can be hard to measure and eventually implement. For instance, it is likely to be very difficult to make employment locations accessible within 15 minutes, and the 30-minute city might be a better measure of accessibility to jobs[13]. In the latter case, it would be more appropriate to evaluate public transport together with active modes, as an integrated transportation solution. Other daily destinations such as supermarkets, cafes, parks, or sports facilities might be a better foundation for the 15-minute city concept, as these are often spread more widely across a city and, ideally, should be accessible by walking and cycling. In either case, some relevant destinations might be more important than others—for instance education and health in comparison to leisure and recreation. However, the 15-minute city concept does not distinguish them in any way, which could be done by giving different weights to different opportunity types. In addition, it should also be stressed that there are significant differences between perceived and physical walking distances, so the 15-min distance might not necessarily translate into the same physical distance for all individuals or for all places. Indeed, other impedance functions such as a cumulative-gaussian function are more adequate to measure pedestrian accessibility[12].

Regardless of these limitations of the 15-minute city concept, (active) accessibility has gained importance in the past few years as a fundamental policy goal[14]. The focus on accessibility is justified since one of the main purposes of transportation is to provide access to places, opportunities, and human activities and not to increase mobility per se[15,16]. However, in addition, transportation is identified as an important source of imbalance,

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imposing unequal access conditions for distinct sociodemographic and economic groups, as well as for distinct territories[17]. Previous research has shown distinct consequences of transportation on health[18,19], the environment[20], and quality of life[21], revealing that the least benefited groups carry the heavier burdens[22]. Therefore, by looking at transportation from a non-utilitarian distributive-justice perspective, i.e., how benefits and burdens are distributed in society, the absolute level of accessibility to opportunities stands as a key element for policy making, and its fair distribution throughout society gains in prominence[23–25]. Simply put, by measuring accessibility, it is possible to reveal inequalities that should guide decision-making toward fairness and sustainability, positively affecting people's lives.

Several studies have measured active accessibility in individual cities[8,26–29], and most highlight that the city centre is the most accessible location. However, to the best of our knowledge, there are no comparisons of active accessibility in cities of different countries, nor assessments of their inequalities. This is partly due to the specificities of the methodology that is applied in an individual case study, along with the need to collect data that is specific to the location. Although some methods have been developed to be applied in different locations, for instance, the Walk Score methodology[30,31], at the time of writing (2023) European countries are not included in the dataset. A recent methodology (OSM-WALK-EU)[32] allows the calculation of walkability for European cities but requires computing it within QGIS, making it hard to apply to large datasets of cities. Walkability primarily focuses on the quality of the pedestrian experience and infrastructure within a specific area, while accessibility by foot encompasses a broader concept, considering the ability to reach various destinations, including those in areas with varying levels of walkability. There is also a recent methodology to measure population access to amenities for any city in the world, although currently, only 25 cities have been used[33]. Moreover, although there are some examples of between-cities comparisons of accessibility, they are focused on comparing access to jobs using different transport modes[14], or comparing access to generic services in Europe using the entire road (driving) network[34], but not specifically on pedestrian accessibility. In general terms, these studies show that cities have better accessibility than rural areas and that European and Chinese cities have higher pedestrian accessibility to jobs than cities in other countries.

Therefore, recognizing (multimodal) accessibility as a way to reach environmental and social justice in the urban context, the present paper raises the question: *How unequal are the current pedestrian accessibility conditions in European cities?*

We limited our analysis to pedestrian accessibility within 15 minutes of travel by foot, considering different walking speeds (see Methods for details), and excluded cycling due to possible inconsistencies found in the cycling network[35], and because it would require additional data, which are often non-existent, incomplete or proprietary, such as slope, connectivity and traffic speed[36,37], which may have greater altering effects when analysing cycling behavior if compared to pedestrian (e.g., how much would a change in slope affect their speeds). We adopted two accessibility measures to measure inequality: *Total Destinations*, which measures accessibility to all destinations (a cumulative opportunities measure); and *Variety*, which describes the assortment of accessibility to 10 opportunity types. All opportunities were classified into the following ten destination types (the final classification is available as supplementary material): (1) Education, (2) Supermarkets, markets, and food shops, (3) Healthcare, (4) Sports and recreation, (5) Culture and leisure, (6) Parks and other green areas, (7) Eating and drinking establishments, (8) Retail, (9) Religious, and (10) Public service. These were used in calculations of *Variety* (0 to 10 types accessible), to evaluate patterns of pedestrian accessibility as a function of different combinations of types and count the total number of destinations of each type.

The absence of standards or target values that can be used to evaluate 'sufficient' accessibility, renders cumulative opportunities indicators inadequate to absolutely determine whether a certain location has 'good' or 'bad' accessibility. However, they are a suitable comparative tool to distinguish places with 'high' or 'low' accessibility and can be useful to assess accessibility inequality within cities. The adoption of the *Variety* indicator allows us to evaluate also between cities inequality, although we recognize that the adoption of 10 opportunity types as representing the group of relevant opportunities is open to debate and might not be adequate for all individuals, resembling one of the limitations of the 15-minute city concept pointed above.

The *Variety* indicator was selected to evaluate the added value of accessing additional opportunities and resembles the concept of *Species Richness* often used in Biology[38]. Rather than assuming that all opportunities constitute a homogeneous group, destinations can be grouped into categories and the calculation can focus on how many different opportunity categories can be accessed within a certain travel threshold. The method sees variety as a special type of accessibility, defined as the ease of reaching different opportunities. It can be measured by calculating the number n of access indicators (n being the type of opportunity) and summing them into an overall variety indicator. For instance, it is better to have access to one education facility and one health facility (variety of 2) than having access to two education facilities and no health facilities (variety of 1). Although it does not capture the distinction between a place with several types of opportunities, and a place with only one opportunity of the same type, the variety measure enables direct and straightforward comparisons of locations both within a single city and between different cities, as the reference value is the same for all locations. This within- and between-city indicator, therefore, makes it possible to perform comparative studies such as the one we present here. We have also calculated *Entropy*, but due to the high correlation with *Variety*, we've decided to keep only the Variety indicator as it translates more directly to the 15-minute city concept (see results below).

Our dataset included all European cities with more than 100,000 inhabitants, a total of 585 cities. By choosing European cities as case studies, we acknowledge that we are analyzing cases with relatively high pedestrian accessibility. However, significant differences in accessibility levels might exist within each city, and not all European cities might necessarily reveal high accessibility. To harmonize data within and across different cities, we represented our results as a hexagon grid that covered entire cities and excluded hexagons with no network nodes (our considered origins). This approach overcomes potential biases that might arise from areas with small urban blocks in which the node density is higher than in areas with larger urban blocks, which would result in the overrepresentation of these nodes at the city level. Our analyses relied on open-source software and open-access data, as our aim was to both monitor the future evolution of cities, and allow any other researcher, public official, or politician to be able to measure any other place by replicating our methodology.

RESULTS

Pedestrian accessibility in European cities

Our results reveal considerable differences in pedestrian accessibility across European cities and countries. As shown in Table 1, at the country scale, the mean number of *Total Destinations* varies between 17.5 (Sweden) and 136.4 (Switzerland). Other countries with high values are Ireland (90.9), Austria (80.0), and Luxembourg (75.3). Countries with low mean values include Finland (20.5),

Table 1. Descriptive statistics for accessibility values for the sample of European cities, grouped by country.

									Territorial-based Gini						Population-based Gini						
Country			Total Destinations			Variety			Total Destinations			Variety			Total Destinations			Variety			
	Name	Cities	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Data Points
AT	Austria	5	80.0	55.5	108.0	6.9	6.4	7.5	0.688	0.641	0.739	0.253	0.197	0.304	0.606	0.568	0.667	0.115	0.075	0.167	41746
BE	Belgium	8	55.9	17.6	116.1	6.4	4.6	8.6	0.688	0.579	0.790	0.277	0.118	0.393	0.643	0.486	0.763	0.179	0.046	0.264	64105
BG	Bulgaria	6	31.1	8.5	67.4	3.8	1.9	6.6	0.823	0.688	0.903	0.547	0.296	0.694	0.722	0.594	0.813	0.351	0.163	0.500	55852
CH	Switzerland	6	136.4	67.1	229.3	7.9	6.2	9.6	0.576	0.378	0.709	0.170	0.037	0.298	0.459	0.324	0.531	0.054	0.017	0.100	18235
CY	Cyprus	2	35.4	32.8	38.0	5.2	4.7	5.8	0.719	0.675	0.763	0.398	0.347	0.449	0.593	0.548	0.638	0.186	0.159	0.213	9845
CZ	Czech Republic	6	58.2	29.9	90.0	6.4	5.4	7.8	0.617	0.570	0.648	0.273	0.174	0.353	0.504	0.486	0.520	0.136	0.089	0.184	63172
DE	Germany	80	47.5	12.2	112.8	6.4	4.0	8.4	0.651	0.497	0.808	0.285	0.134	0.484	0.551	0.405	0.669	0.127	0.059	0.223	757291
DK	Denmark	4	50.2	8.6	155.0	4.9	2.5	8.6	0.719	0.567	0.829	0.407	0.113	0.633	0.611	0.451	0.696	0.183	0.043	0.263	70212
EE	Estonia	1	50.8	—	—	6.4	—	—	0.646	—	—	0.258	—	—	0.538	0.538	0.538	0.170	0.170	0.170	10616
EL	Greece	5	65.1	32.8	95.9	5.8	4.5	7.3	0.749	0.670	0.847	0.357	0.243	0.484	0.617	0.491	0.737	0.151	0.059	0.229	38429
ES	Spain	63	66.1	4.9	297.9	5.2	1.5	9.1	0.718	0.382	0.935	0.417	0.084	0.804	0.558	0.302	0.805	0.206	0.019	0.477	283333
FI	Finland	9	20.5	3.8	71.9	3.6	1.2	7.4	0.754	0.623	0.902	0.532	0.203	0.826	0.599	0.511	0.655	0.232	0.088	0.350	200575
FR	France	42	62.8	16.3	153.1	7.0	3.6	8.7	0.646	0.462	0.866	0.257	0.113	0.540	0.596	0.417	0.798	0.126	0.041	0.333	292103
HR	Croatia	4	44.7	27.3	87.1	5.4	4.6	5.9	0.723	0.640	0.793	0.382	0.338	0.461	0.603	0.539	0.676	0.200	0.150	0.245	27834
HU	Hungary	8	27.5	10.9	71.6	4.0	2.7	7.2	0.792	0.662	0.849	0.520	0.230	0.651	0.665	0.599	0.699	0.267	0.107	0.358	76555
IE	Ireland	2	90.9	69.9	111.9	8.5	8.4	8.7	0.600	0.595	0.606	0.118	0.112	0.125	0.605	0.595	0.614	0.063	0.058	0.068	10353
IS	Iceland	1	32.7	—	—	4.4	4.4	4.4	0.704	—	—	0.473	—	—	0.467	0.467	0.467	0.158	0.158	0.158	11334
IT	Italy	45	42.9	6.6	162.1	5.3	2.1	8.8	0.719	0.554	0.866	0.396	0.106	0.700	0.503	0.326	0.684	0.111	0.015	0.280	249846
LT	Lithuania	4	28.1	23.5	41.7	4.7	3.8	5.2	0.715	0.680	0.798	0.423	0.376	0.512	0.639	0.570	0.735	0.309	0.262	0.400	39330
LU	Luxembourg	1	75.3	—	—	7.2	—	—	0.676	—	—	0.240	—	—	0.540	0.540	0.540	0.063	0.063	0.063	3206
LV	Latvia	1	48.9	—	—	5.6	—	—	0.703	—	—	0.359	—	—	0.614	0.614	0.614	0.200	0.200	0.200	17187
MT	Malta	1	52.1	—	—	7.9	—	—	0.520	—	—	0.173	—	—	0.394	0.394	0.394	0.079	0.079	0.079	2599
NL	Netherlands	30	52.5	21.4	133.5	5.8	3.7	8.0	0.657	0.476	0.790	0.307	0.156	0.463	0.547	0.372	0.682	0.163	0.085	0.260	223996
NO	Norway	4	45.2	30.8	65.5	5.5	4.4	7.5	0.654	0.515	0.720	0.350	0.186	0.442	0.553	0.487	0.656	0.139	0.088	0.207	70770
PL	Poland	38	41.4	16.2	85.6	5.5	3.8	7.2	0.689	0.565	0.814	0.368	0.230	0.513	0.566	0.438	0.679	0.198	0.106	0.293	273930
PT	Portugal	16	37.4	6.2	142.4	5.5	2.7	9.3	0.673	0.474	0.859	0.349	0.068	0.619	0.516	0.337	0.713	0.152	0.029	0.298	77703
RO	Romania	24	33.5	7.7	75.9	5.2	2.5	7.7	0.672	0.514	0.806	0.419	0.190	0.705	0.543	0.440	0.635	0.249	0.119	0.395	70830
SE	Sweden	12	17.5	3.3	78.1	2.9	1.5	7.7	0.798	0.596	0.891	0.608	0.158	0.743	0.567	0.476	0.669	0.239	0.099	0.340	248141
SI	Slovenia	2	24.2	21.6	26.7	4.2	3.6	4.7	0.770	0.728	0.813	0.476	0.429	0.522	0.572	0.549	0.596	0.173	0.159	0.186	17746
SK	Slovakia	2	54.2	44.8	63.6	5.1	4.6	5.6	0.768	0.742	0.794	0.416	0.373	0.460	0.538	0.531	0.545	0.117	0.116	0.117	21241
UK	United Kingdom	153	51.7	5.2	593.4	6.6	1.7	9.9	0.601	0.267	0.880	0.267	0.010	0.735	0.488	0.239	0.669	0.112	0.004	0.343	998963
Total dataset		**585**	**50.3**	**3.3**	**593.4**	**5.6**	**1.2**	**9.9**	**0.665**	**0.267**	**0.935**	**0.334**	**0.010**	**0.826**	**0.541**	**0.239**	**0.813**	**0.153**	**0.004**	**0.500**	**4347078**

Bold values, in the last row indicate the totals per indicator (columns).

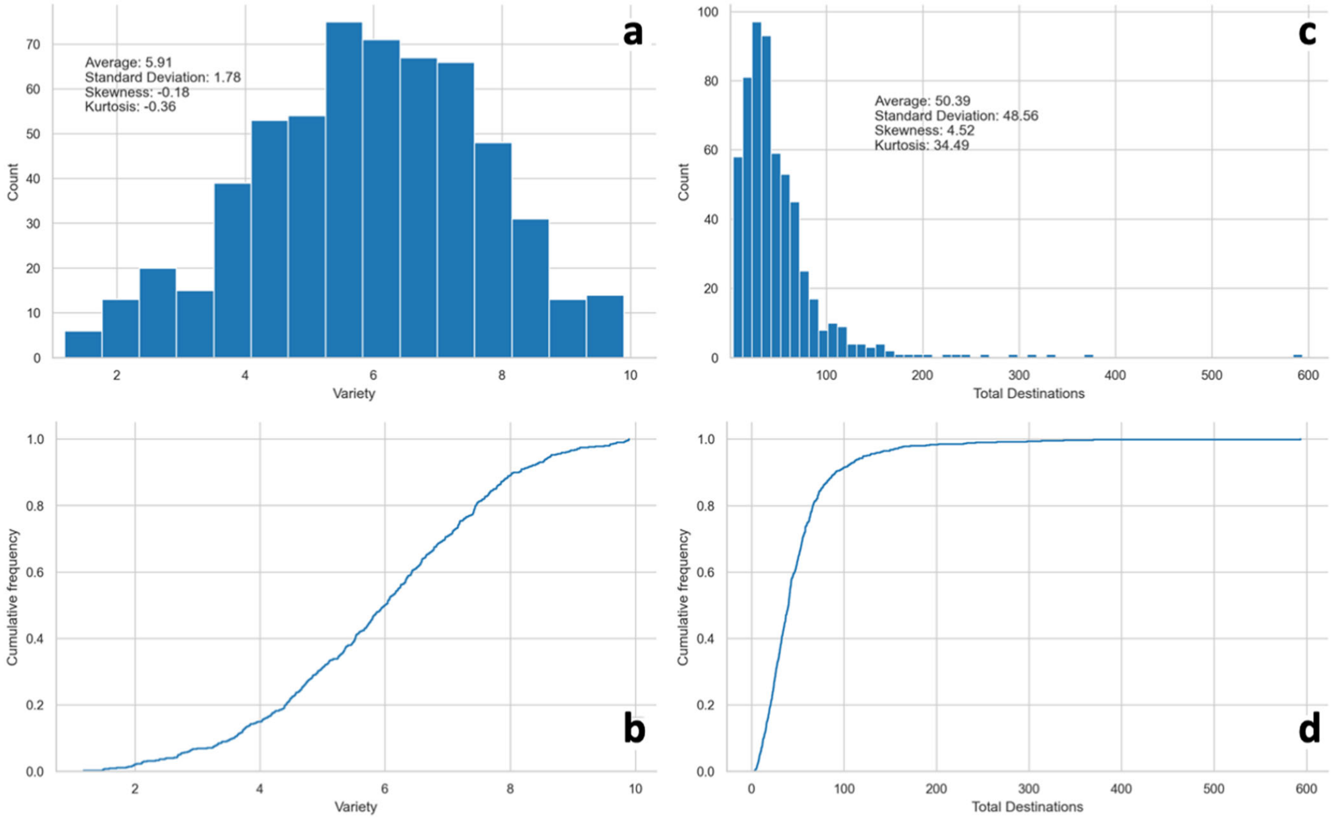


Fig. 1 **Histograms and cumulative frequency charts.** The proposed graphs illustrate the values for total destinations and variety counts for the analyzed European cities. Figures (**a**) and (**b**) illustrate the variety values, while (**c**) and (**d**) correspond to total destination counts.

Slovenia (24.2), and Hungary (27.5). The pattern for *Variety* is somewhat similar, with Sweden (2.9) being the lowest and Ireland (8.5) the highest. Values are high for Malta (7.9), Switzerland (7.9), Luxembourg (7.2), and low for Finland (3.6), Bulgaria (3.8), and Hungary (4.0).

Accessibility across cities

Our analysis of accessibility at the city level (mean values for each city) highlighted a very wide range of values for *Total Destinations* (from 3.3 to 593.4). The distribution is positively skewed (4.532), with a mean of 98.79. Nearly 50% of cities have mean values that are below 50, while less than 10% of them have a mean that is above 100. On the other hand, the distribution for *Variety* is approximately normal, ranging from 1.18 to 9.90, with a mean of 5.907. Mean *Variety* scores range from 1.18 (Kuopio, FI) to 9.90 (Islington, UK), while only approximately 11% of all cities (65 cities) have a *Variety* score that is above 8 (Fig. 1).

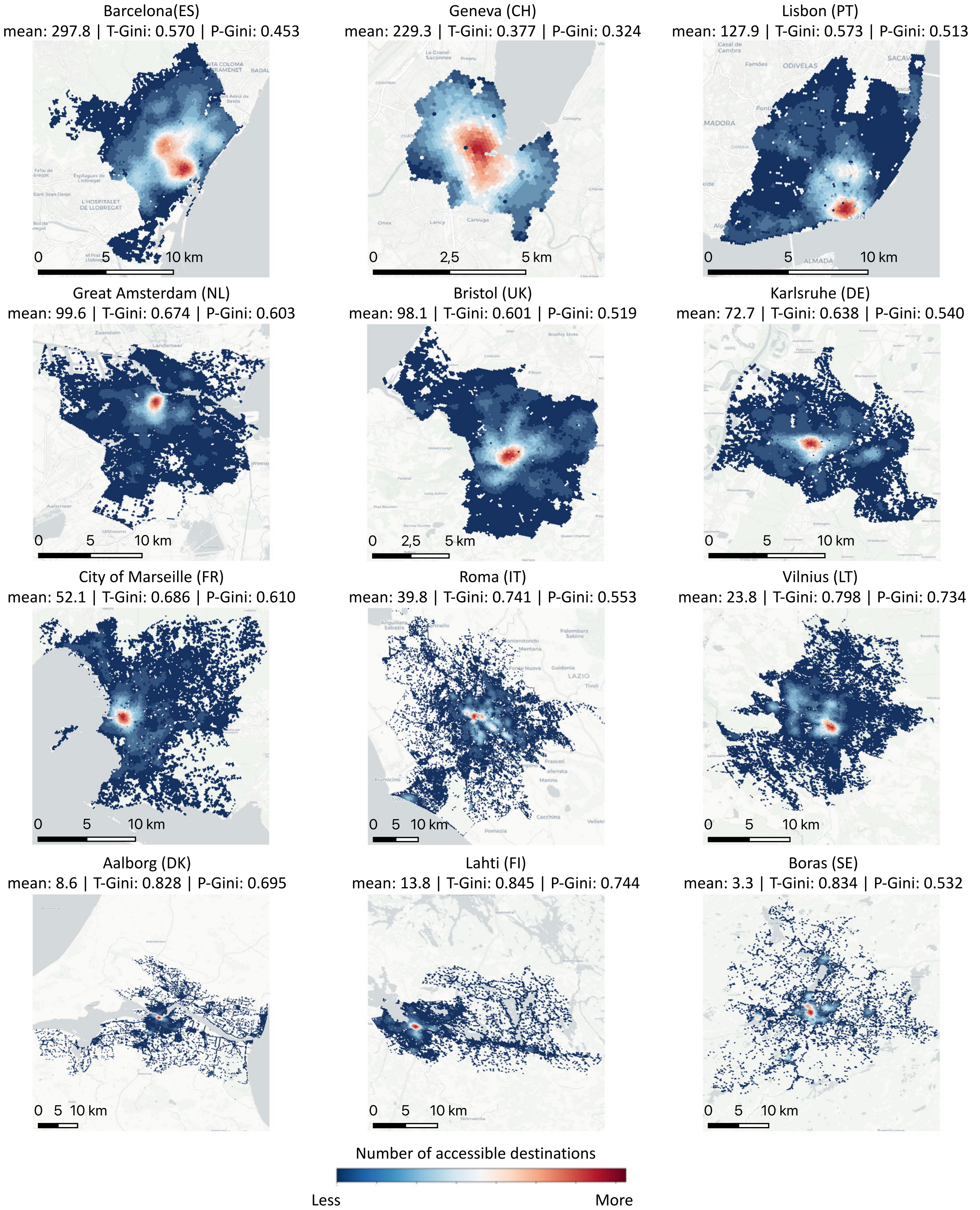
Total Destinations and Variety describe different accessibility patterns for European cities. The analysis of Total Destinations revealed that means are very high for some cities, and they can be considered outliers within the overall pattern of pedestrian accessibility. On the other hand, the distribution of Variety is normal, and no clear outliers can be identified. In fact, two cases emerge: 6.8% of cities have very low mean Variety scores (3 or less), while 11% have very high mean scores (8 or more). Overall, if we take the Variety indicator as a benchmark, European cities seem to be still far from the 15-minute "ideal". It is noteworthy, however, that, the impact of varying administrative borders might have a significant impact on accessibility measurements, as some cities (e.g.,: many cities in Finland, or Sweden) present unpopulated areas. Therefore, population density should be carefully analyzed.

Accessibility within cities

A deeper analysis provides insight into whether the spatial distribution of accessibility within a city varies. In fact, even a city with low mean accessibility might contain several distinct areas with high accessibility. Given the size of our dataset, it would be impossible to map all the cities. Therefore, we selected a sample of 12 cities in different European countries for further analysis. The analysis of the maps revealed different spatial patterns for both *Total Destinations* and *Variety* (Figs. 2 and 3).

Total Destinations tend to be characterized by a single hotspot in the city centre, where most opportunities are located. Although a polycentric pattern is identified in some cities (Barcelona, Lisbon, Rome, and Vilnius are good examples), even in these cases a principal hotspot can be identified. Moreover, the score for the hotspot varies widely—from around 70 (Boras, SE) or 220 (Lahti, FI)—to over 2,350 (Greater Amsterdam, NL). These disparities emphasize that the indicator is a useful way to evaluate within-city comparisons, but also that it is a relatively useless way to evaluate between-city comparisons.

On the other hand, our analysis of *Variety* revealed that high accessibility can be found in areas beyond the city's hotspot(s), even if there are fewer total opportunities. This is clearly illustrated by the cases of Greater Amsterdam, Marseille, Rome, and Vilnius, where *Variety* scores reveal other areas with good local accessibility, in addition to the hotspot identified by the *Total Destinations* score. In particular, the analysis revealed that in all cities there is at least one place in which *Variety* is maximum (10 different opportunity types). Moreover, in 3.4% (20) cities the mean score is higher than 9, and in 7.7% (45) cities the score is between 8 and 9 (see supplementary material for the full table). In summary, while all European cities have at least one area where residents have pedestrian access to a *Variety* of opportunities



Barcelona(ES)
mean: 297.8 | T-Gini: 0.570 | P-Gini: 0.453

Geneva (CH)
mean: 229.3 | T-Gini: 0.377 | P-Gini: 0.324

Lisbon (PT)
mean: 127.9 | T-Gini: 0.573 | P-Gini: 0.513

Great Amsterdam (NL)
mean: 99.6 | T-Gini: 0.674 | P-Gini: 0.603

Bristol (UK)
mean: 98.1 | T-Gini: 0.601 | P-Gini: 0.519

Karlsruhe (DE)
mean: 72.7 | T-Gini: 0.638 | P-Gini: 0.540

City of Marseille (FR)
mean: 52.1 | T-Gini: 0.686 | P-Gini: 0.610

Roma (IT)
mean: 39.8 | T-Gini: 0.741 | P-Gini: 0.553

Vilnius (LT)
mean: 23.8 | T-Gini: 0.798 | P-Gini: 0.734

Aalborg (DK)
mean: 8.6 | T-Gini: 0.828 | P-Gini: 0.695

Lahti (FI)
mean: 13.8 | T-Gini: 0.845 | P-Gini: 0.744

Boras (SE)
mean: 3.3 | T-Gini: 0.834 | P-Gini: 0.532

Fig. 2 **Total destinations accessible within a 15-minute walk.** This figure shows a selection of 12 of the 585 analyzed cities. Underneath each map, there is a statistical summary, indicating the average value, and the inequality levels for territorial and populational-based GINI coefficients.

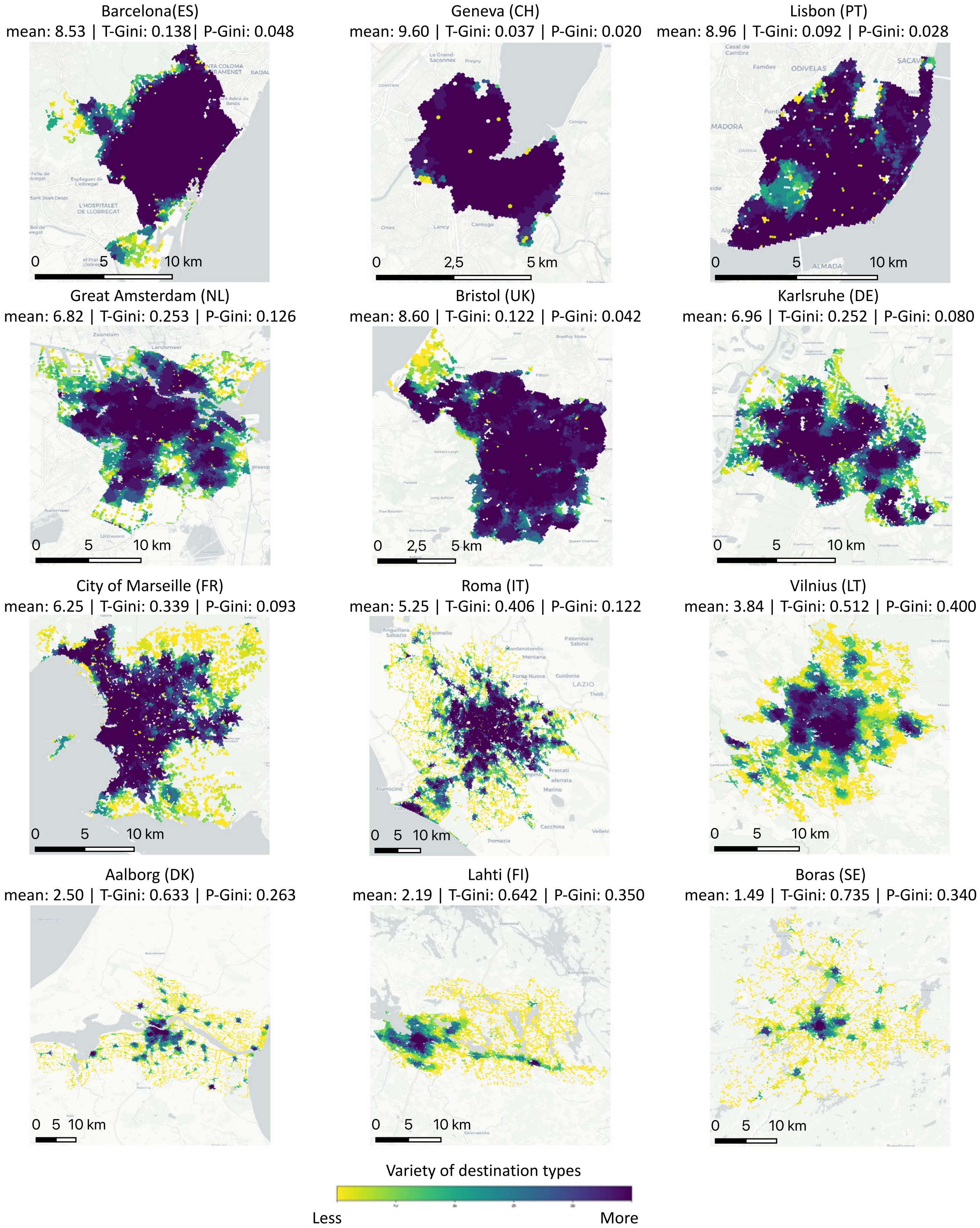


Fig. 3 Variety of destination types (min 0, max 10) accessible within a 15-minute walk. This figure shows a selection of 12 of the 585 analyzed cities. Underneath each map, there is a statistical summary, indicating the average value, and the inequality levels for territorial and populational-based GINI coefficients.

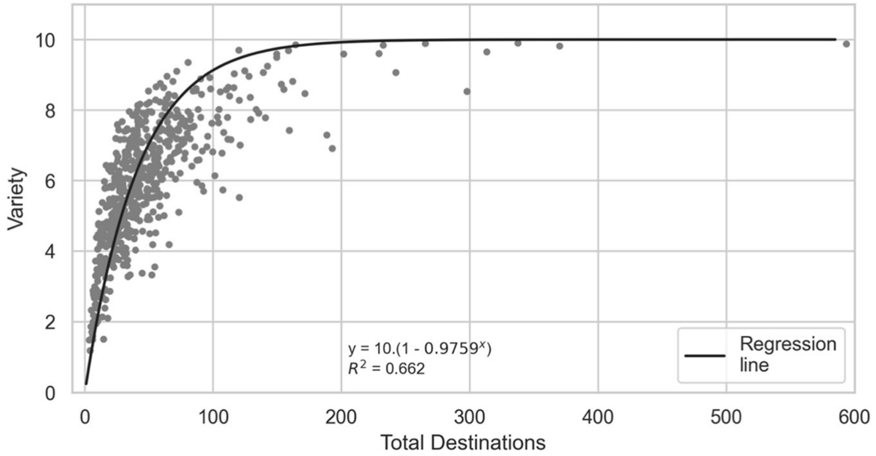


Fig. 4 **Total Destinations and Variety dispersion diagram.** The diagram shows the correlation of Total Destinations and Variety across 585 European cities. The fitted curve demonstrates an upward exponential decay trend.

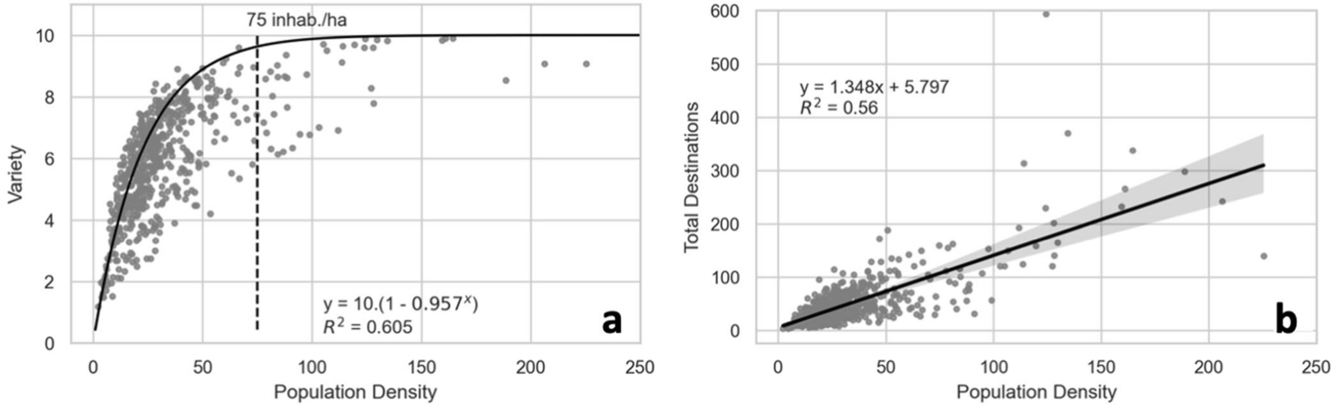


Fig. 5 **Correlation between Population density and the Variety and Total Destinations values.** Diagrams showing the relationship between population density and **a** Variety and **b** Total Destinations. In **a** it is possible to see the 75 inhabits./ha line indicating the point from which density increments translate into less Variety gain.

within 15 minutes, this is far from being possible for all areas of a city.

The relationship between *Total Destinations* and *Variety* for all cities follows an exponential decay upward function ($r^2 = 0.662$) (Fig. 4). *Variety* scores for several cities are lower than predicted by the trendline, suggesting that some cities feature several opportunities of the same type: the total number of accessible destinations is high, but there is a relative lack of *Variety* of opportunities.

Accessibility, population size, and density

Given the known importance of population density for accessibility and travel behavior[39–42], we compared our two accessibility indicators with the city's population density. This analysis identified a linear relationship between *Total Destinations* and density ($r^2 = 0.56$) (Fig. 5). On the other hand, we found a relationship between density and *Variety* ($r^2 = .605$) that follows the shape of an exponential decay upward function, with the upper limit defined by the total number of *Variety* classes (10).

As observed in Fig. 5, the relation between density and *Variety* is characterized by diminishing returns, which suggests that population density is not enough by itself to increase variety, and other factors such as the urban structure and local economy are likely to be equally important. From this, we infer that it is possible to achieve a high level of *Variety* without a particularly high population density. Acknowledging that density can have both positive and negative externalities (beyond a certain value), our results suggest that a certain density level is needed to increase *Variety*, but, at the same time, beyond that value, density has a lesser effect in increasing variety. Although finding an 'ideal' density value is beyond the scope of this article, our results suggest that this threshold stands around 7500 inhabits./km^2 or 75 res/ha, which seems sufficient to achieve good variety. Another work[43] indicates a limit of 92 res/ha, although their line or reasoning was not pointed toward the Variety indicator.

A remaining question is whether this dependency is observed among all groups of cities. To evaluate these effects, we clustered the cities in population-size and density-level classes and proceeded with the analysis of *Variety* levels. Results indicate that larger cities (over 1 million residents) have higher average *Variety* levels, while smaller cities (100,000 to 250,000 residents) have both the lowest and highest absolute values. As a general trend, and for all size groups, higher-density levels are associated with higher *Variety* values. Low-density cities (< 25 inhabits./ha) have *Variety* scores smaller than 7.5, while high-density cities (> 75 inhabits./ha) have *Variety* scores above 6.2. Within the two more populous groups, there are four clear outliers, identified in Fig. 6.

Gini coefficients for Total destinations and Variety

Our analysis of accessibility inequality in European cities is given by Gini coefficients for the two indicators, both territory-based and population-based measurements. The territory-based

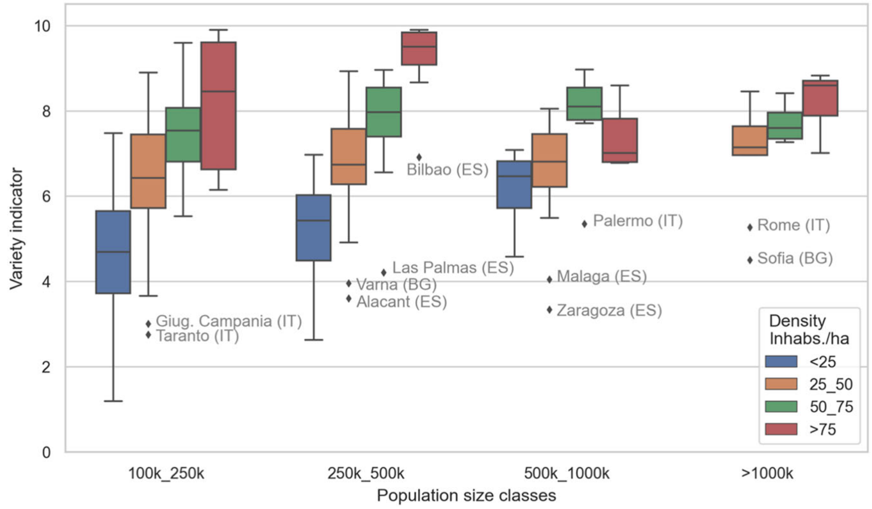


Fig. 6 Variety levels for population-size and density-level (inhabits./ha) classes of cities. The boxplot diagram shows that larger cities tend to present lower Variety variance and higher average Variance levels.

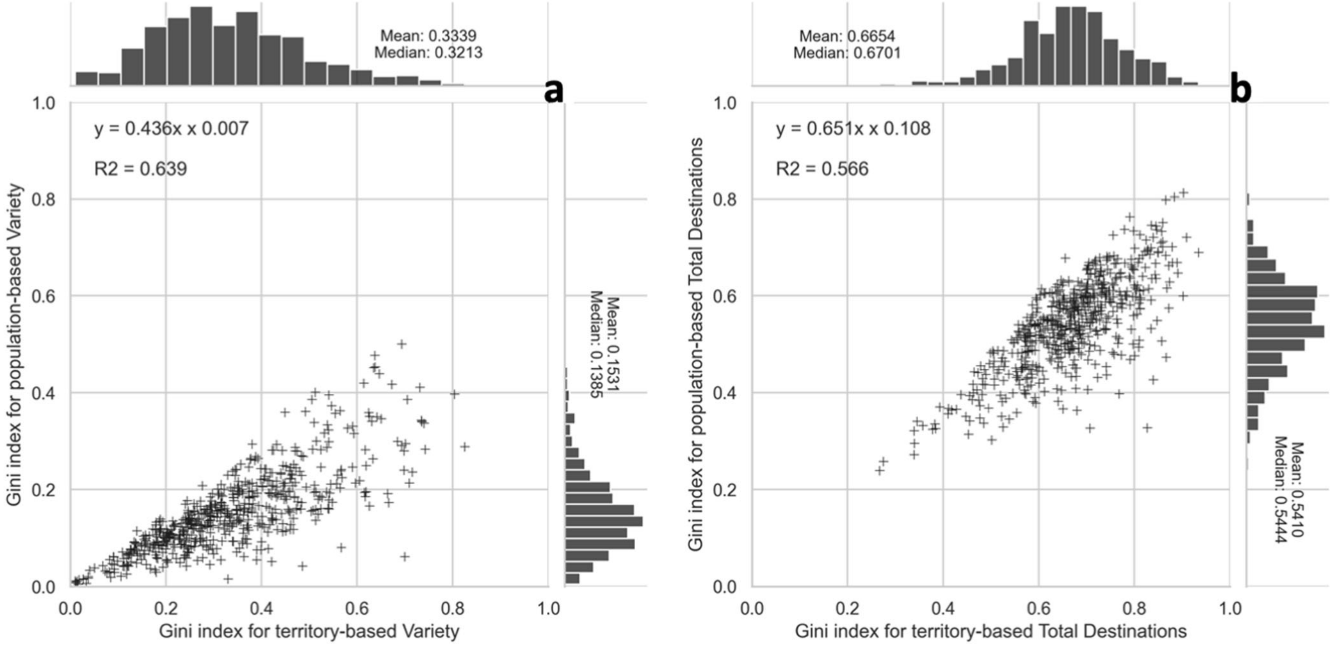


Fig. 7 Comparison between the population and territory-based inequality levels of Variety and Total Destinations. The dispersion diagrams indicate the relationship between P-Gini and T-Gini coefficients for both Variety **a** and Total Destinations **b** accessibility indicators, accompanied by the histograms for each variable.

indicator evaluates the inequality between the Gini levels associated with the grid cells used to discretize the territory (henceforth referred to as T-Gini), whereas the population-based indicator compares the accessibility levels for each person living in the city (and in specific grid cells), covering the whole population (referred to as P-Gini) – see average values in Table 1. Results show that, for both *Variety* and *Total Destinations*, values for P-Gini are significantly lower when compared to values for T-Gini. For *Total Destinations* the mean Gini value drops from 0.665 to 0.541, moreover, the *Variety* inequality coefficient drops from 0.333 to 0.153. It is also notable that *Variety* inequality is systematically lower than *Total Destinations* inequality in all cities (Fig. 7).

When we compare accessibility mean values and inequality levels, results show a significant negative relationship between absolute values of *Variety* and both T-Gini ($r^2 = .971$) and P-Gini ($r^2 = .656$) coefficients (Fig. 8). On the other hand, results show a low correlation between *Total Destinations* values with both T-Gini ($r^2 = .207$) and P-Gini ($r^2 = .083$) coefficients. These results suggest that, despite the observed correlation between the two inequality indicators, cities with less inequality tend to have higher variety, but not necessarily a greater total number of accessible destinations.

As before, the inequality levels are not the same for the different population and density groups of cities. Larger cities present the lowest average P-Gini coefficients for the *Variety* indicator, where the highest value is 0.238. Inequality in smaller cities presents a wider amplitude of P-Gini coefficients, ranging from 0.006 to 0.499. A similar situation occurs with T-Gini values. Smaller cities present T-Gini coefficients that range from 0.010 to 0.825, while T-Gini for larger cities is always lower than 0.480 (Fig. 9). Except for T-Gini coefficients for cities in the 500k to 1000k population, cities with higher density levels are associated with

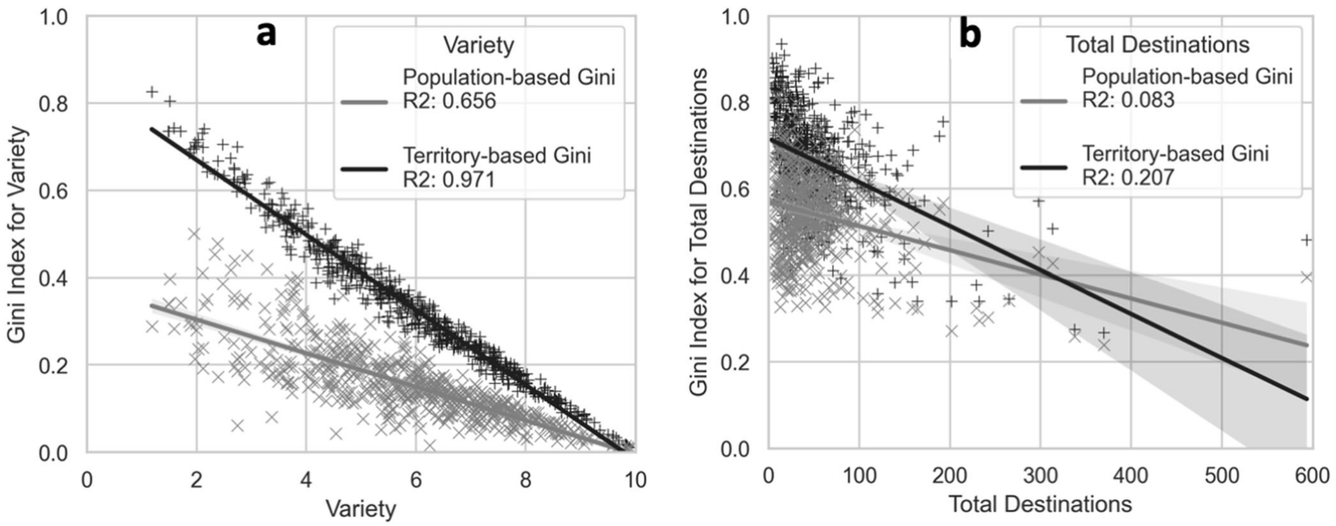


Fig. 8 How Variety and Total Destinations levels correlate to their inequality levels? Dispersion diagrams showing the relationship between territory and population-based Gini coefficients and both **a** Variety and **b** Total Destinations accessibility indicators for 585 European cities.

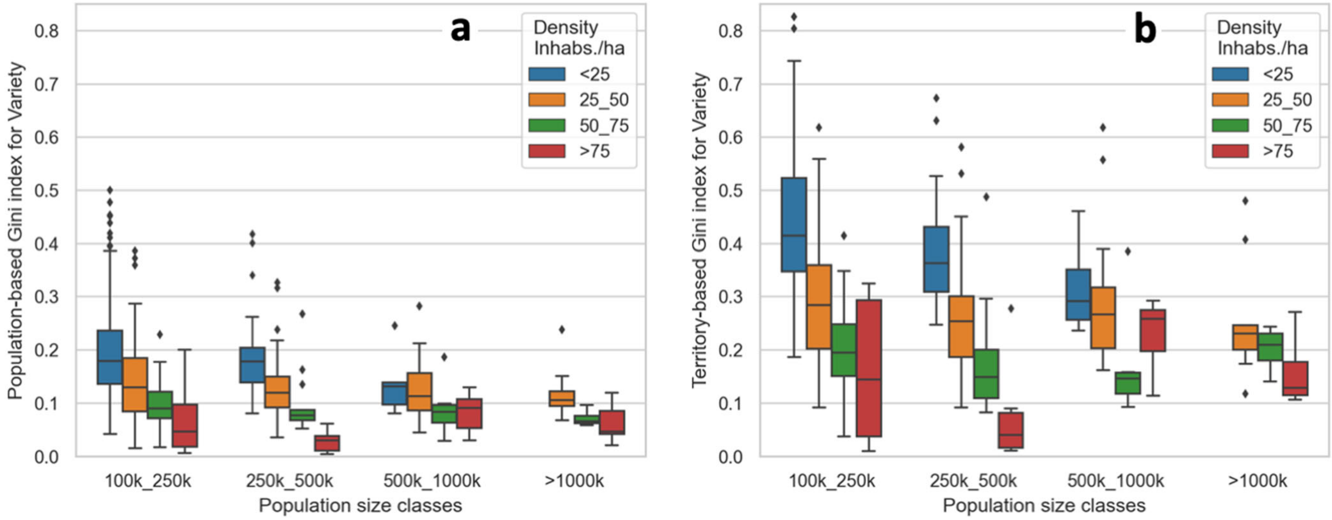


Fig. 9 Population and Territory-based inequality levels distribution for distinct city sizes and density levels. Boxplot comparison between **a** population-based and **b** territory-based Gini coefficients for Variety levels of cities with distinct density and population sizes.

lower inequality levels of both P-Gini and T-Gini, within all population classes.

It is important to indicate that there are many outliers for the Population-based Gini index for Variety (Fig. 9a), mostly in cities below 500k inhabitants. The cities below 250k inhabitants represented as outliers were Stara Zagora, Ruse, Burgas (Bulgaria), Lieida, Telde, Elche, Almería, Albacete (Spain), Baia Mare, Ramnicu Valcea, Suceava (Romania). For cities with populations between 250k and 500k inhabitants, the outliers point to the cities of Varna (Bulgaria), Murcia, Córdoba, Alacant (Spain), and Vilnius (Lithuania), and finally, still in the same population group but with densities between 50 and 75 inhabits./ha, we have Plovdiv (Bulgaria), Las Palmas de Gran Canaria (Spain), and Redbridge (UK).

DISCUSSION

Our results show that pedestrian accessibility conditions are quite diverse in our sample of European cities. In the absence of a normative accessibility value, computing accessibility to total destinations is a useful way to analyze within-city differences and identify places with better and poorer accessibility. However, classifying places as having 'good' or 'bad' accessibility is less clear, as scores are only relevant within a certain city. In our sample of European cities, the range of scores was very wide—from a little over 70 to more than 2500 destinations are accessible within a 15-minute walk, each constituting an accessibility hotspot within a city. On the other hand, our *Variety* indicator proved to be a useful measure of within-city differences and a way to compare the accessibility of different cities. Here again, we found a diverse set of situations in our sample, with mean values ranging from 1.2 to 9.6 (out of a maximum of 10). Furthermore, our indicator made it possible to identify locations within cities with high Variety, even if mean overall scores for the whole city were low.

Results highlight an exponential decay upward relationship between *Total Destinations* and *Variety*, suggesting diminishing marginal returns between them. Cities with high mean *Variety* can have high or low mean scores for *Total Destinations*, while cities with low mean *Variety* scores have low mean scores for *Total*

Destinations. In other words, there is evidence to support that it is possible to achieve *Variety* when a certain minimum number of Total Destinations are accessible and that this is necessary to increase urban diversity. However, beyond a certain threshold, having access to more opportunities does not necessarily increase access to different opportunities.

Geographically, the two indicators reveal different accessibility patterns at the city level. For most cities, the *Total Destinations* indicator tends to highlight a single hotspot in the city centre, while the *Variety* indicator reveals several polycentric patterns. Accessibility hotspots identified by the *Variety* indicator reveal that, even with a relatively small number of total destinations accessible by foot, there are places within cities that provide highly diverse accessibility. In these locations, individuals can walk to different opportunities and satisfy different needs. Therefore, our findings show that a place with high local pedestrian accessibility, measured as access to different opportunities, does not require numerous opportunities, which is an important result in the context of the development and implementation of urban policies.

Our findings are important in the context of urban sustainability policies as, in practice, it may be impossible to design a city in which all places allow access to the same number of opportunities, notably due to the known tendency of competing activities to aggregate in certain locations to reach a larger market[44]. On the other hand, it may be reasonable to aim to design a city in which there is (nearly) equal access to different types of opportunities. This could be achieved by designing a city that features several diverse centralities. Organized into an appropriate spatial pattern, it would become possible to access at least one centrality in under 15 minutes of walking from anywhere in the city.

The relationship between our two accessibility indicators and population density also merits discussion. While we found a linear association between *Total Destinations* and density, the relationship between *Variety* and density followed an exponential decay upward relation. Here again, although our results emphasize the importance of density in improving accessibility, they raise the question of the 'ideal' density value for a city, as it appears that beyond a certain threshold, the disadvantages may outweigh the benefits. Although a relationship can be identified for mean values, this does not suggest that an entire city should have the same density. In any case, our study makes it clear that it is very difficult to offer good pedestrian accessibility with low density, and, at the same time, that density above a certain value may contribute little to an increase in pedestrian accessibility and might create undesired externalities and/or costs.

Regarding inequality levels, it is not a surprise that European cities are very diverse, both between and within cities. The term "inequality" carries a lot of weight, which requires a careful consideration of what these numbers mean. In practice, the decision to adopt P-Gini over T-Gini as an inequality measure depends on the context. It is expected that the population spatial distribution follows (up to a certain degree) that of either the built environment or the activities. In general, more people mean more buildings as well as more activities. Such a relation follows a power-law scaling (allometry)[45]. Territorial inequality results may be useful for policymaking when decisions are not demand-based (for instance, based on coverage), while population-based inequality measures might help when dealing with individuals' rights and expectations. Therefore, these inequality results are as useful as the policy-making process requires.

The cities presented great differences between the mean Gini for both *Variety* and *Total Destinations*. Both T-Gini and P-Gini differences were noticeable, with the coefficients associated with *Variety* being systematically lower than those of Total Destinations. The unforeseen result is that while *Variety* levels are strongly associated with inequality levels, Total Destinations are not. A possible explanation for higher total destination inequality is that activities' locational decisions follow the logic of spatial agglomeration or clustering, as described by various well and long-known theories such as the bid-rent theory[46] as a direct economic effect of accessibility. The clustering effect would generate an availability disparity. On the other hand, Variety is affected not only by activities' locational choices but also by people's locational choices. People try to balance out the accessibility to needed activities. As a result, the Variety inequality is lowered, as more people locate closer to where activities are.

Nonetheless, overall, and for all cities, population inequality is lower than territorial inequality. Indeed, we found that P-Gini is always lower than T-Gini, suggesting that residential location decisions tend to alleviate inequality levels. This difference is especially evident in the case of the diversity of reachable activities (the *Variety* indicator) rather than in the total number of reachable activities (the Total Destinations indicator). Accessibility as given by the *Variety* indicator tends to be more polycentric, which can be interpreted as a more egalitarian spatial pattern. This finding highlights the importance of increasing the mixture of activities to achieve pedestrian accessibility equality across a city, which aligns with the arguments of the 15-minute city concept.

Finally, it is important to question the feasibility of adopting a single arbitrary threshold, such as a 15-minute walk, to measure accessibility to different opportunity types[47,48], as the willingness to walk to an opportunity is related to the trip's purpose and the type of opportunity[49–51]. Individuals might be more willing to walk to more specialized opportunity types such as art, music, and hobbies shops, or to (central) locations where several opportunities can be found. Therefore, actual and desired walking distances might be both a cause and a consequence of the larger catchment areas of these places[52], which, in turn, makes them more geographically concentrated and therefore less accessible by foot. In addition, any x-minute threshold translates into different spatial thresholds for different individuals, based on their characteristics and capabilities. It is a clear and straightforward concept, but far from being an inclusive, universal one. Consequently, using several distinct thresholds to measure accessibility to distinct opportunity types might be a more appropriate approach, and should be tested in the future. Other future research should include cycling accessibility and include other cities in other parts of the world.

METHODS

Data sources

This research relies exclusively on open-access data, and the following datasets were used. The administrative boundaries of European cities were obtained from Eurostat/ GISCO geographical data (©EuroGeographics), specifically, the Urban Audit 2020 dataset (version 01/01/2020). The latter contains the boundaries of cities, greater cities, and functional urban areas as defined by the EC-OECD. We selected the 'city' division to identify cities, along with all 'greater city' divisions that did not include a 'city', to include capitals such as Brussels and Athens. In this paper, all these areas are included as a 'city', regardless of whether they are a city or a greater city.

Population data were obtained from Eurostat for the period 2011–2020, and the most recent figure was used given data availability for each city. The final population dataset consisted of 864 European cities in 31 countries. As we only analyzed cities with 100,000 inhabitants or more, our final dataset consisted of 585 cities, which ensured that at least one city from each country was included.

The street network for the sample of cities was obtained from OpenStreetMap (OSM). The pedestrian network was obtained using the Pandana python library (v. 0.6.1)[53], which specifically excludes all street segments that are not walkable, and creates a graph from OSM data that makes it possible to compute fast origin-destination (O-D) matrices.

To measure accessibility, origins were set as all nodes in the pedestrian network, following the Pandana methodology. Destinations were obtained with the PYROSM python library (v. 0.6.0)[54], after downloading OSM data for each country on 15 June 2021. We selected all points of interest (POIs) whose OSM tags—a combination of a *key* and a *value*—had the following keys: amenity, craft, leisure, office, shop, and tourism. All POIs whose "access" was identified as "no", "private" or "customers" were excluded from the dataset. Given that some important destinations are not represented as POIs, but as buildings (polygons), we extracted all data related to non-residential buildings and represented them by their centroid. To avoid double counting the same destination, we only considered buildings that were not within a polygon with another tag. This was very commonly the case for hospitals, universities, and other large facilities, which OSM shows as several buildings, and as a polygon that represents the facility (the POI itself). Finally, to control for edge effects, we selected destinations by considering a linear buffer of 1 km for each city boundary.

To create the necessary hexagon grids, Uber's Hexagonal Hierarchical Spatial Index (H3) was selected for this purpose (https://github.com/uber/h3). Level 10 hexagons were used, which have a mean edge length of 65.908 meters and a mean area of 15,047.5 m^2. Our samples of cities had between 439 (Santa Coloma de Gramenet, Spain) and 56,941 (Berlin, Germany) hexagons and our final city dataset consisted of 4,347,078 observations.

Accessibility measures

There are two broad approaches for measuring active accessibility: place-based (focused on the accessibility of places) or individual-based (focused on accessibility for certain individuals), and initiatives can also be divided into those that target pedestrian or cycling accessibility. In turn, active travel can either provide direct access to an opportunity by walking or cycling exclusively, or it can be integrated into a sustainable travel ecosystem. In the latter case, it allows access to another sustainable travel mode (public transport, for instance) in what is designated the first or last mile of a complex travel chain. Like other accessibility measures, active accessibility is a function of four interrelated components: land use, transportation, temporal, and individual[55]. In the context of urban planning, a place-based perspective is normally adopted, and it is typically measured as access to several relevant opportunities (land use), via active travel (transportation), regardless of the time of day (temporal), for everyone (individual). It should be noted that although other built environment factors are also important for active accessibility, notably safety, topography, or aesthetic features, they are rarely taken into account in current instruments and measures[4].

The focus on place-based accessibility is justified by its ability to allow easy comparisons of different places and/or different moments[13]. Although the temporal component is normally absent in active accessibility measures, it changes significantly throughout the day, not only because many opportunities are closed at some times of day, but also due to safety concerns. Likewise, by ignoring the individual component, the final measure might be overstating active accessibility for some individuals. Indeed, by focusing on specific groups, such as the elderly, children, or people with reduced mobility[26,27,56], previous research has revealed different accessibility patterns, either because travel speeds are slower and/or because certain physical elements can constitute barriers or hindrances to travel. Of particular importance is the assumed walking speed. In fact, walking speed is known to be highly associated with certain individual features, in particular age, increasing from childhood to adulthood and decreasing from adulthood to old age, gender (higher in men), and disability. An example is the assumed 1.2 m/s walking speed required to utilize pedestrian crossings, which was revealed to be very high for 84% of older men and 93% of older women in the UK, whose mean walking speed was found to be 0.9 m/s[57]. In summary, the assumption of a mean walking speed to measure pedestrian accessibility is, even if implicitly, a parameter of the individual component of accessibility, which will inevitably (even if inadvertently) overstate accessibility for children, older people, and individuals with disabilities.

To calculate pedestrian accessibility for all nodes in a city's network, we used a cumulative opportunities measure, given by the formula:

$$A_i = \sum_{j=1}^{n} O_j f(C_{ij}), \quad \begin{cases} f(C_{ij}) = 1, if\ C_{ij} \leq \delta \\ f(C_{ij}) = 0, if\ C_{ij} > \delta \end{cases} \tag{1}$$

where A_i is the accessibility of node i, O_j represents the opportunities found at node j, C_{ij} is the cost of traveling between i and j, and δ is the threshold considered in the accessibility measure.

Although other measures might evaluate pedestrian accessibility more accurately, and may be less sensitive to the chosen threshold[12], any other measure would significantly increase the computational time needed to achieve our objectives. Given that a pedestrian's walking speed varies significantly as a function of age, slope, weather, and other perceived and subjective features of the built environment, the 15-minute threshold can be expected to change significantly depending on the considered group. Given that no slope information was collected, and the accessibility measure is intended to represent an overall accessibility measure for all individuals, we measured accessibility using three different constant mean walking speeds across the entire pedestrian network (0.7 m/s, 0.9 m/s and 1.1 m/s), as the threshold δ to represent a 15-minute walk – which translates into 630 m, 810 m and 990 m respectively. The final reported accessibility value for each location is the mean value of the value obtained with each of these three values.

We calculated two accessibility indicators:

- The total number of destinations, regardless of type.
- The *Variety* of destinations, represented as the number of different types of destinations accessible within a 15-minute walk, regardless of the number of destinations of each type – values can range between 0 and 10.

Final accessibility results, calculated for each street network node, were then combined for the respective hexagon. The final score for the hexagon corresponds to the value of the node that is closest to the hexagon's centroid.

Entropy was an alternative concept that we considered during the analysis. It simultaneously evaluates the number and proportion of each opportunity type (or land use category)[40,58]. However, it is seldom used in urban planning, despite its sound theoretical background[59], probably due to the difficulty in identifying specific planning measures to increase entropy. Moreover, we have found a strong correlation ($r^2 = 0.955$) between Variety and Entropy measurements for our sampled cities. Therefore, we decided to adopt a simple variety indicator that only focuses on the number of opportunity types, and ignores the proportion of each type, as we consider it would be a planning goal that is easier to define and interpret and could be used to determine progress with respect to the 15-minute city concept.

Analysis of inequality

Our analysis of inequality was based on calculating pseudo-Gini coefficients for both accessibility variables (*Total Destinations* and *Variety*). Given that population is not equally distributed across cities, we calculate two distinct coefficients: Territorial-based Gini (T-Gini) and Population-based Gini (P-Gini). The T-Gini coefficient was calculated considering all observation points (hexagons) for each city. It, therefore, represents the 'spatial inequality' of the two indicators calculated. In order to calculate P-Gini, we started by estimating the number of residents per hexagon, using the Global Human Settlement Layer (GHS population grid - R2023)[60], constituting a 'weight' for each hexagon. Both indicators were calculated using PySAL (v.2.1.0)[61].

Limitations

Some limitations should be noted regarding our results. First, although our accessibility threshold was selected to be consistent with the 15-minute concept, other travel time thresholds might lead to different results – the Modifiable Area Unit Problem[62,63]. In addition, we transformed travel time into travel distance assuming a constant travel speed. To minimize this problem, we took into consideration extreme values to represent both fast and slow-paced walking patterns. For the sake of general calculations, we used the average value as stated in section 4.2. This might be relevant if a particular demographic group is selected (for instance, elderly people). Second, it is possible that the exclusive use of OpenStreetMap data[64] might influence the reliability of our findings, and we recognize that it might be an incomplete representation of all the opportunities that could exist in a city. Nevertheless, this is the only available dataset that makes it possible to perform the comparative evaluation of a sample of European cities presented here. On the other hand, our combination of open-access data with open-source software means that it is possible for anyone to perform the same analysis for any place in the world, and this was one of our explicit objectives. Third, the delimitation of cities provided by Eurostat/GISCO is far from homogeneous for all European countries. Some cities are delimited as a single unit (e.g., Brussels or Athens), while others are considered as a group of smaller cities (e.g., London), which might bias our results. However, we are not aware of any other official delimitation of European cities that could be adopted for our analyses. Finally, and probably the most important limitation, is that our results do not reflect real walking conditions, as they ignore the detailed features of the pedestrian network (sidewalks, crossings, pedestrian bridges, etc.). While we are aware that these micro-scale elements constitute a limitation to walking[56], here again, there are no available data that would allow us to analyze all European cities. Therefore, we recommend that our results should be interpreted as 'potential' pedestrian accessibility, and not necessarily real-life conditions in our sample of European cities.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

DATA AVAILABILITY

The POI classification and the table with results for each city are available as supplementary material. Maps for each city can be provided upon email request to the authors.

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REFERENCES

1. Buehler, R., Pucher, J., Gerike, R. & Götschi, T. Reducing car dependence in the heart of Europe: lessons from Germany, Austria, and Switzerland. *Transp. Rev.* **37**, 4–28 (2017).
2. Newman, P. & Kenworthy, J. *The end of automobile dependence: How cities are moving beyond car-based planning*. (Island Press, 2015).
3. European Commission (EC). *Sustainable and Smart Mobility Strategy – putting European transport on track for the future*. (European Comission, 2020).
4. Vale, D. S., Saraiva, M. & Pereira, M. Active accessibility: a review of operational measures of walking and cycling accessibility. *J. Transp. Land Use* **9**, 209–235 (2016).
5. Shashank, A. & Schuurman, N. Unpacking walkability indices and their inherent assumptions. *Heal. Place* **55**, 145–154 (2019).
6. Da Silva, D. C., King, D. A. & Lemar, S. Accessibility in practice: 20-minute city as a sustainability planning goal. *Sustain* **12**, 1–20 (2020).
7. Moreno, C. The 15 min-city: for a new chrono-urbanism! http://www.moreno-web.net/the-15-minutes-city-for-a-new-chrono-urbanism-pr-carlos-moreno/ (2019).
8. Weng, M. et al. The 15-minute walkable neighborhoods: measurement, social inequalities and implications for building healthy communities in urban China. *J. Transp. Heal.* **13**, 259–273 (2019).
9. Jacobs, J. *The Death and Life of Great American Cities*. (Vintage Books/Random House, 1961).
10. Healey, P. On Creating the 'City' as a Collective Resource. *Urban Stud* **39**, 1777–1792 (2002).
11. Hägerstrand, T. What about people in Regional Science. *Pap. Reg. Sci. Assoc.* **24**, 7–21 (1970).
12. Vale, D. S. & Pereira, M. The influence of the impedance function on gravity-based pedestrian accessibility measures: a comparative analysis. *Environ. Plan. B Urban Anal. City Sci.* **44**, 740–763 (2017).
13. Levinson, D. M. *The 30-Minute City: Designing for Access*. (Network Design Lab, 2020).
14. Wu, H. et al. Urban access across the globe: an international comparison of different transport modes. *npj Urban Sustain* **1**, 1–9 (2021).
15. Handy, S. Planning for accessibility: in theory and in practice. in *Access to Destinations* (eds. Levinson, D. M. & Krizek, K. J.) 131–147 (Elsevier, 2005).
16. Van Wee, B. & Geurs, K. T. Discussing equity and social exclusion in accessibility evaluations. *Eur. J. Transp. Infrastruct. Res.* **11**, 350–367 (2011).
17. Lucas, K. Transport and social exclusion: Where are we now? *Transp. Policy* **20**, 105–113 (2012).
18. Mackett, R. L. & Thoreau, R. Transport, social exclusion and health. *J. Transp. Heal.* **2**, 610–617 (2015).
19. Mueller, N. et al. Health impact assessment of active transportation: a systematic review. *Prev. Med. (Baltim)* **76**, 103–114 (2015).
20. Pucher, J. & Buehler, R. Why Canadians cycle more than Americans: a comparative analysis of bicycling trends and policies. *Transp. Policy* **13**, 265–279 (2006).
21. Banister, D. *Inequality in Transport*. (Alexandrine Press, 2018).
22. Pereira, R. H. M., Schwanen, T. & Banister, D. Distributive justice and equity in transportation. *Transp. Rev.* **37**, 170–191 (2017).
23. Lucas, K., van Wee, B. & Maat, K. A method to evaluate equitable accessibility: combining ethical theories and accessibility-based approaches. *Transportation (Amst)* **43**, 473–490 (2016).
24. Martens, K., Bastiaanssen, J. & Lucas, K. Measuring transport equity: Key components, framings and metrics. in *Measuring Transport Equity* (eds. Lucas, K., Martens, K., Di Ciommo, F. & Dupont-Kieffer, A..) 13–36 (Elsevier Inc., 2019). https://doi.org/10.1016/b978-0-12-814818-1.00002-0.
25. Martens, K. *Transport Justice*. (Taylor & Francis, 2017).
26. Gaglione, F., Cottrill, C. & Gargiulo, C. Urban services, pedestrian networks and behaviors to measure elderly accessibility. *Transp. Res. Part D Transp. Environ.* **90**, 102687 (2021).
27. Moura, F., Cambra, P. & Gonçalves, A. B. Measuring walkability for distinct pedestrian groups with a participatory assessment method: a case study in Lisbon. *Landsc. Urban Plan.* **157**, 282–296 (2017).
28. Pereira, M. F., Almendra, R., Vale, D. S. & Santana, P. The relationship between built environment and health in the Lisbon Metropolitan area – can walkability explain diabetes' hospital admissions? *J. Transp. Heal.* **18**, 100893 (2020).
29. Talavera-Garcia, R. & Soria-Lara, J. A. Q-PLOS, developing an alternative walking index. A method based on urban design quality. *Cities* **45**, 7–17 (2015).
30. Duncan, D. T., Aldstadt, J., Whalen, J., Melly, S. J. & Gortmaker, S. L. Validation of walkscore® for estimating neighborhood walkability: an analysis of four US metropolitan areas. *Int. J. Environ. Res. Public Health* **8**, 4160–4179 (2011).
31. Hall, C. M. & Ram, Y. Walk score® and its potential contribution to the study of active transport and walkability: a critical and systematic review. *Transp. Res. Part D Transp. Environ*. https://doi.org/10.1016/j.trd.2017.12.018 (2018).
32. Fina, S. et al. OS-WALK-EU: An open-source tool to assess health-promoting residential walkability of European city structures. *J. Transp. Heal.* **27**, 101486 (2022).
33. Boeing, G. et al. Using open data and open-source software to develop spatial indicators of urban design and transport features for achieving healthy and sustainable cities. *Lancet Glob. Heal.* **10**, 907–918 (2022).

34. Kompil, M., Jacobs-Crisioni, C., Dijkstra, L. & Lavalle, C. Mapping accessibility to generic services in Europe: a market-potential based approach. *Sustain. Cities Soc.* **47**, 101372 (2019).
35. Ferster, C., Fischer, J., Manaugh, K., Nelson, T. & Winters, M. Using OpenStreetMap to inventory bicycle infrastructure: a comparison with open data from cities. *Int. J. Sustain. Transp.* **14**, 64–73 (2020).
36. Sorton, A. & Walsh, T. Bicycle stress level as a tool to evaluate urban and suburban bicycle compatibility. *Transp. Res. Rec. 1438*, 17–24 (1994).
37. Winters, M., Teschke, K., Brauer, M. & Fuller, D. Bike Score®: Associations between urban bikeability and cycling behavior in 24 cities. *Int. J. Behav. Nutr. Phys. Act.* **13**, 1–10 (2016).
38. Gotelli, N. J. & Colwell, R. K. Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. *Ecol. Lett.* **4**, 379–391 (2001).
39. Cervero, R., Sarmiento, O. L., Jacoby, E., Gomez, L. F. & Neiman, A. Influences of built environments on walking and cycling: lessons from Bogotá. *Int. J. Sustain. Transp.* **3**, 203–226 (2009).
40. Cervero, R. & Kockelman, K. Travel demand and the 3Ds: density, diversity, and design. *Transp. Res. Part D* **2**, 199–219 (1997).
41. Lee, C. & Moudon, A. V. The 3Ds+R: Quantifying land use and urban form correlates of walking. *Transp. Res. Part D Transp. Environ.* **11**, 204–215 (2006).
42. Vale, D. S. & Pereira, M. Influence on pedestrian commuting behavior of the built environment surrounding destinations: a structural equations modeling approach. *Int. J. Sustain. Transp.* **10**, 730–741 (2016).
43. Shatu, F. & Kamruzzaman, M. Determining Optimum Design Density for 20-minute Neighbourhoods. *Transp. Find*. 1–7 https://doi.org/10.32866/001c.27391 (2021).
44. Seong, E. Y., Lim, Y. & Choi, C. G. Why are convenience stores clustered? The reasons behind the clustering of similar shops and the effect of increased competition. *Environ. Plan. B Urban Anal. City Sci.* **49**, 834–846 (2022).
45. Adhikari, P. & de Beurs, K. M. Growth in urban extent and allometric analysis of West African cities. *J. Land Use Sci.* **12**, 105–124 (2017).
46. Alonso, W. *Location and land use: toward a general theory of land rent*. (Harvard University Press, 1964).
47. Logan, T. M. et al. Evaluating urban accessibility: leveraging open-source data and analytics to overcome existing limitations. *Environ. Plan. B Urban Anal. City Sci.* **46**, 897–913 (2019).
48. Larsen, J., El-Geneidy, A. M. & Yasmin, F. Beyond the quarter mile: re-examining travel distances by active transportation. *Can. J. Urban Res. Can. Plan. Policy* **19**, 70–88 (2010).
49. Yang, Y. & Diez-Roux, A. V. Walking distance by trip purpose and population subgroups. *Am. J. Prev. Med.* **43**, 11–19 (2012).
50. Millward, H., Spinney, J. & Scott, D. Active-transport walking behavior: destinations, durations, distances. *J. Transp. Geogr.* **28**, 101–110 (2013).
51. Perchoux, C. et al. Walking, trip purpose, and exposure to multiple environments: a case study of older adults in Luxembourg. *J. Transp. Heal.* **13**, 170–184 (2019).
52. Dolega, L., Pavlis, M. & Singleton, A. Estimating attractiveness, hierarchy and catchment area extents for a national set of retail centre agglomerations. *J. Retail. Consum. Serv.* **28**, 78–90 (2016).
53. Foti, F., Waddell, P. & Luxen, D. A Generalized Computational Framework for Accessibility: From the Pedestrian to the Metropolitan Scale. *4th Transp. Res. Board Conf. Innov. Travel Model*. 1–14 (2012).
54. Tenkanen, H. HTenkanen/pyrosm: v0.6.0. https://doi.org/10.5281/ZENODO.4279527 (2020).
55. Geurs, K. T. & Van Wee, B. Accessibility evaluation of land-use and transport strategies: review and research directions. *J. Transp. Geogr.* **12**, 127–140 (2004).
56. Vale, D. S., Ascensão, F., Raposo, N. & Figueiredo, A. P. Comparing access for all: disability-induced accessibility disparity in Lisbon. *J. Geogr. Syst.* **19**, 43–54 (2017).
57. Asher, L., Aresu, M., Falaschetti, E. & Mindell, J. Most older pedestrians are unable to cross the road in time: A cross-sectional study. *Age Ageing* **41**, 690–694 (2012).
58. Tsai, Y.-H. Quantifying urban form: compactness versus 'sprawl'. *Urban Stud* **42**, 141–161 (2005).
59. Wilson, A. G. *Entropy in Urban and Regional Modelling*. (Pion, 1970).
60. Schiavina, M., Freire, S. & MacManus, K. GHS-POP R2022A—GHS Population Grid Multitemporal (1975-2030). *Eur. Comm. Jt. Res. Cent*. (2022).
61. Rey, S. J. & Anselin, L. PySAL: A Python library of spatial analytical methods. *Rev. Reg. Stud* **37**, 5–27 (2007).
62. Openshaw, S. *The modifiable areal unit problem*. *Concepts and Techniques in Modern Geography 38* (Geobooks, 1983).
63. Clark, A. & Scott, D. Understanding the impact of the modifiable areal unit problem on the relationship between active travel and the built environment. *Urban Stud* **51**, 1–16 (2013).
64. Basiri, A., Haklay, M., Foody, G. & Mooney, P. Crowdsourced geospatial data quality: challenges and future directions. *Int. J. Geogr. Inf. Sci* **33**, 1588–1593 (2019).

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COMPETING INTERESTS

The authors declare no competing interests.

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