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Research Article

Utilizing OpenStreetMap data to measure and compare pedestrian street lengths in 992 cities around the world

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Abstract
Although pedestrian or car-free streets can powerfully produce multiple benefits for urban quality of life, sustainability, and public health, very few studies have quantified and analysed their networks in cities all around the world. Given that, in this paper we use OpenStreetMap (OSM) data and integrate the EU and OECD definition of cities to create comparable global indicators concerning the length of pedestrian streets. Our methodology combines OSM data queries and spatial analysis techniques in R. Due to serious inconsistencies observed in other walking-related OSM annotations we use only the pedestrian tag. The results reveal a chasm in car-free development mainly between Southern and Western European cities and their peers in other continents. Since the latter further underlines clear differences in sustainable urban and transport planning cultures around the world, policy analysts and decision-makers can use these findings in order to support data-driven car-free urban planning and thus alleviate the detrimental effects of car traffic on the environment and human health.

Highlights:

- *Comparable urban indicators for car-free streets around the world are presented and analyzed*
- *OSM and R programming are combined to measure the length of pedestrian streets in several cities*
- *European urban areas have the most extensive networks of car-free streets in the world*
- *Cities from North America & Oceania showed on average significantly smaller pedestrian street lengths compared to Europe*
- *Paris, Barcelona, Madrid, Rotterdam & Valencia have the most extensive networks of pedestrian streets in the world*

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1. INTRODUCTION

A city without cars is likely the most utopian urban mobility scenario for the future, particularly if we take into account research transportation forecasts that predict the presence of two billion motor vehicles worldwide by 2030 (Gross, 2016). However, the reasons for partially car-free and pedestrian-friendly cities are more pressing than ever (Nieuwenhuijsen & Khreis, 2016). The climate change threat, the reduction of transport-related greenhouse gas emissions, and the prevention of premature mortality in cities from physical inactivity, air, and noise pollution are probably the most persuasive arguments to lead the transition from planning for traffic conditions to planning for pedestrians (Gross, 2016; Nieuwenhuijsen & Khreis, 2016; Soni & Soni, 2016). Pedestrianization schemes that recalibrate road space are promising urban strategies, resulting in the improved quality of streetscapes, higher footfall rates, and reduced car traffic (Cairns et al., 2002). Several studies have been carried out in recent years that attempt to explain the positive effects of car-free living and planning on urban livability (Bartzokas-Tsiompras et al., 2021a; Nieuwenhuijsen & Khreis, 2016; Rydningen et al., 2017) as well as to quantify the unfair road space (Nello-Deakin, 2019) or streetscape features (Bartzokas-Tsiompras et al., 2020a, 2021b; Bartzokas-Tsiompras & Photis, 2021c) distribution among the population.

Yet, to create accurate and comparable indicators regarding cities' actions to support non-car dependent lifestyles, it is essential to have worldwide, free, and complete geospatial data about pedestrian infrastructure. Openstreetmap.org (OSM), provides volunteered geographic information (VGI) for the planet and constitutes a valuable online street database (Barrington-Leigh & Millard-Ball, 2017). In the current work, we aim to draw upon OSM road data to shed light on which cities across the globe contain the most extended pedestrian street network.

1.1 PEDESTRIAN STREETS AND THE CITY

The concepts of car-free cities and pedestrian zones are not new (Hass-Klau, 2015; Soni & Soni, 2016; Topp & Pharoah, 1994). For example, Hass-Klau (2015), reported that 21 German cities already had small-scale pedestrian streets in 1955 (on average 400- 900 meters); most of them were located in the more developed region, at that time, of North Rhine-Westphalia. In the early 1990s, Topp and Pharoah (1994) described five European plans for car-free city centres that were used by urban authorities to improve the quality of public spaces and boost retail. Wikipedia lists a great number of car-free locations and streets from more than 50 countries around the world (https://en.wikipedia.org/wiki/List_of_car-free_places, Accessed: 20/07/19). Nonetheless, Hass-Klau (2015) in her book *The pedestrian and the city* covers the evolution of pedestrian-friendly urban development, and discusses in detail the politics and policies that concern walking and pedestrians. Other extensive reviews about the rationale and the impact of car-free urban development on healthy city living can be found in Nieuwenhuijsen and Khreis (2016) and the review of Glazener et al. (2022), while Soni and Soni (2016) analysed the difficulties and benefits that resulted from a pedestrianization plan. Nevertheless, a recent article published in *Environment and Planning B* indicated that socially active squares and pedestrian streets in central Europe are highly stimulating walking environments (Hillnhütter, 2021). For instance, the research demonstrated that pedestrians' head movements increase by 71% and looking down decreases by 54%, compared to public spaces designed for auto-vehicles and car traffic. Additionally, Meng & Kang (2015) estimated that crowded commercial pedestrian streets in China can mask several typical sound sources, such as traffic noise, transit systems, music from shops etc. Further, pedestrian streets can reduce vehicular traffic by 11% (Cairns et al., 2002) and increase the average time of active travel by 41 minutes per week (Aldred et al., 2019).

Recently, cities that hope to mitigate the adverse environmental and public health impacts stemming from car-based lifestyles have decided to create road diets (Sadik-Khan & Solomonow, 2017) and to provide more space for pedestrians, cyclists, and public transit. Helsinki and Oslo announced ambitious plans for extensive car-free schemes in their central cities (Nieuwenhuijsen & Khreis, 2016). Similarly, other metropolises worldwide, such as Paris, Milan, Chengdu, Masdar, Brussels, Dublin, Copenhagen, Bogota, and Hyderabad, have already started to promote a mixed set of measured and aggressive transportation measures that aim to restrict car access and encourage active mobility (e.g. car-free days, bicycle lanes, reduced parking spaces, etc.). The most emblematic pedestrianization example of our era, though, is the closing of Broadway to motorized traffic around Times Square in New York City. The redesign of the road has shown significant economic benefits for businesses, higher pedestrian and cycling rates, and decreased pedestrian injuries (Sadik-Khan & Solomonow, 2017). However, the emphasis on car-free policies should not be taken for granted. As partisan politics change, urban mobility is impacted. For example, the new conservative government in Madrid considers cars a part of the city's cultural identity and intends to dismantle previous plans that restricted car accessibility in the town centre (O'Sullivan, 2019). As soon as this scheme was announced, people started to protest, indicating their passionate demand for car-free cityscapes (O'Sullivan, 2019). Even so, pedestrianization plans should be comprehensive, including preventive measures for vulnerable groups and businesses, as they can trigger side effects, i.e., gentrification, noise pollution, etc.(Sadik-Khan & Solomonow, 2017).

Within the academic literature on this subject, injustices in road space distribution are a recent focus (Nello-Deakin, 2019). We have evidence that people continuously underestimate the mobility space of cars in cities and, in turn, this perception supports unsustainable transport planning policies (Szell, 2018). Nello-Deakin (2019) used GIS cartography to measure the proportion of road space per travel mode in Amsterdam, as a means to discuss the problematic fairness of road space distribution in the city. He demonstrated that 51% of transport space is distributed to cars (including 10% for parking), while 40% and 7% are provided for pedestrians and bicycles respectively (Nello-Deakin, 2019). Indeed, the measurement and comparison of mobility spaces in cities is an intriguing research topic for GIS researchers that can help to assess land use and urban transport. To this end, Szell and Bogner developed, with the aid of Moovel lab, the open-source online platform What the Street!?, in order to answer the question 'How do new and old mobility concepts change our cities?' (https://github.com/move-lab/lab-whatthestreet, Accessed: 20/03/21). The platform uses OSM data to quantify and visualize the mobility spaces of cars, trains, and bicycles, and compares the results in 23 cities with their modal share statistics, highlighting the privileged distribution of space towards motorized transport. However, What the Street!? platform does not include pedestrian space assessments since OSM lacks sidewalk data in numerous cities. Inspired by Szell's (2018) work, the current study will demonstrate a simple method of utilizing OSM data in R that quantifies the length of the typical pedestrian thoroughfare in cities, meaning shopping or residential pedestrian streets.

1.2 OPENSTREETMAP (OSM)

OSM (https://www.openstreetmap.org) started at University College London in 2004 as a free editable vector map of the world, in which transportation networks and the built environment are included. Now it is the largest crowdsourced VGI web-platform, with more than 5.5 million users and 5 billion free spatial data (https://wiki.openstreetmap.org/wiki/Stats, Accessed: 20/07/19). So far, OSM has been the primary data source for multiple applications and services (e.g. disaster management, environmental monitoring, site selection, navigation, games, etc.). It has also captured the growing interest of many GIS scientists (Barrington-Leigh & Millard-Ball, 2017). However, scholarly attention has been focused on answering questions about the quality of the contributed geographic data (Barrington-Leigh & Millard-Ball, 2017; Haklay, 2010), as volunteers are mostly amateur geographers who collect heterogeneous data. The most common issue of VGI data quality is comprehensiveness, although problems of consistency and positional accuracy also exist. Haklay (2010) pointed out that the lack of coverage in many underdeveloped or developing regions, where people do not have the necessary education or income for the equipment, is an essential limitation of

OSM data usage in multi-country or multi-city comparisons. Recently, a study from one developing nation, Turkey, analysed the spatial evolution of Turkish OSM and demonstrated that population density, literacy level, and the Human Development Index are the best proxies for the spatial bias in OSM data uploads in different regions of the country (Zia et al., 2019). Furthermore, in wealthier places within Western societies there are also significant variances in data coverage, even among neighbourhoods with different incomes. For example, Haklay (2010) revealed that in the poorest neighbourhoods of England, the coverage rate of OSM roads was 46%, while for higher-income neighbourhoods, the same rate was 76%.

In 2017, Barrington-Leigh and Millard-Ball (2017) assessed the entirety of the worldwide OSM road network and found that it was 83% complete, with more than 40% of countries (even in the developing world) listing fully mapped street networks. They also showed that countries with better internet connections tend to have more complete road networks, and that extremely low-density areas and high-density cities are the best mapped. A study from China (Zhang et al., 2015), where OSM activities are considered illegal, indicated that Chinese OSM road density and the diversity of road types are very high in 30.3% of cities (e.g. Shanghai, Macao, Hong Kong Shenzhen, Beijing). Yet, data quality and assessments of specific OSM street types and non-motorized modes of transportation are inadequate.

Regarding pedestrian-related OSM data quality assessments, we identified only a few studies (Zielstra et al., 2013; Zielstra & Hochmair, 2012). Indeed, it is a much more difficult task to assess the quality of OSM's pedestrian segments data, as corresponding governmental and commercial datasets are still rare for many countries and cities worldwide. However, in the US a research study of 70 urbanized areas revealed that, although OSM failed to fully capture motorized traffic roads, the pedestrian-related OSM street data were more detailed when compared with the TIGER/Line national dataset (Zielstra et al., 2013). Also, Zielstra and Hochmair (2012) analysed the completeness of OSM pedestrian street data by comparing OSM-based shortest routes for walking with their equivalents from other proprietary or national datasets for two US and two German cities. Namely, Miami, San Francisco, Berlin, and Munich. Results showed that OSM is a promising data source for pedestrian research since it always provided shorter or equal length paths for pedestrians when compared with all other datasets.

2. DATA AND METHODOLOGY

2.1 OSM PEDESTRIAN STREET DATA

OSM geographic data have three elements: nodes (point features), ways (linear features), and relations (the relationship between two or more nodes/ways). Tags describe each element and every tag includes two fields: a 'key' (the feature type) and a 'value' (information about the key). For instance, *highway=residential* indicates a road line (highway) in a residential area. Concerning pedestrian infrastructure in OSM tags, there are six relevant categories (*key=highway*), including pedestrian, footway, path, sidewalk crossing, steps, etc. (https://wiki.openstreetmap.org/wiki/Map_Features, Accessed 22/7/2019). The majority of these annotations use technical jargon and have incredibly subtle differences in their definitions. As a result, a non-specialist user may encounter difficulties understanding their unique nature and often incorrectly applies street tags to inappropriate roads. This issue is well-known in the OSM community as the Path Controversy (https://wiki.openstreetmap.org/wiki/Path_controversy, Accessed 22/7/2019), and it has led to significant inconsistencies in OSM pedestrian data. One study analysed whether the combined annotations for OSM objects have been attributed according to the OSM wiki guidance to demonstrate that the agreement between tags, in a global sample of 40 cities, was average to poor (Davidovic et al., 2016). Notably, for the footway and path tags, the compliance was about 95% and 92% poor respectively.

Figure 1. Incomplete usage of highway=footway for sidewalks in Saint Petersburg, Russia *(Source: overpass-turbo.com).*

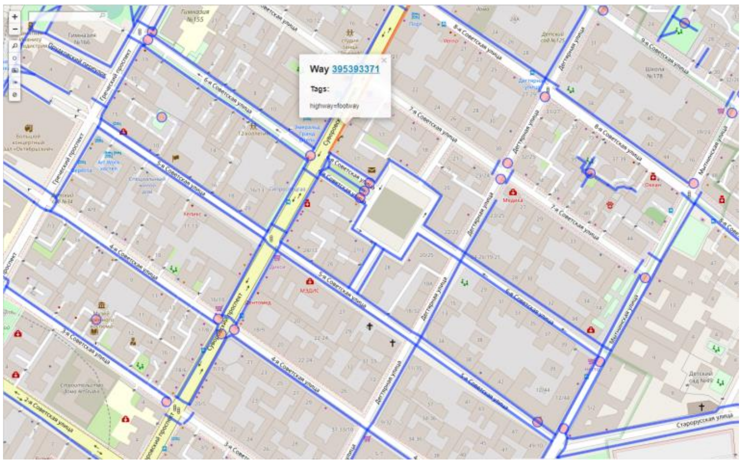


Figure 2. Correct usage of highway=footway and footway=sidewalk in Toronto, Canada *(Source: overpass-turbo.com).*

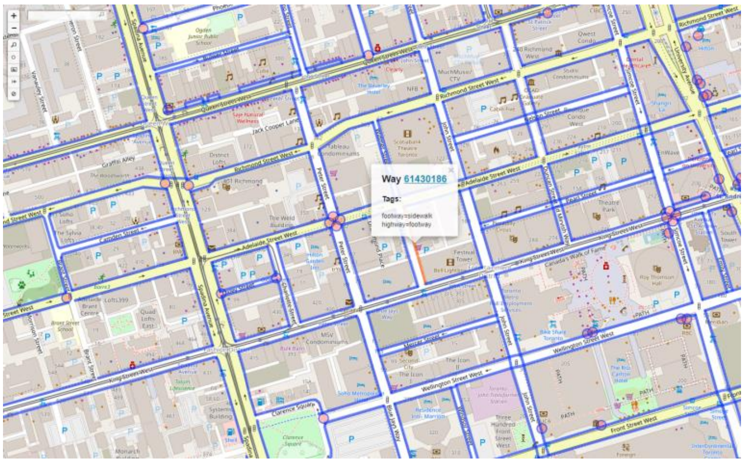
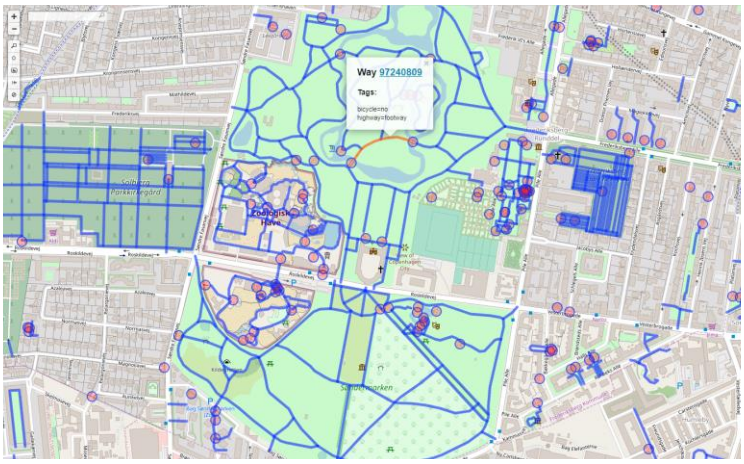
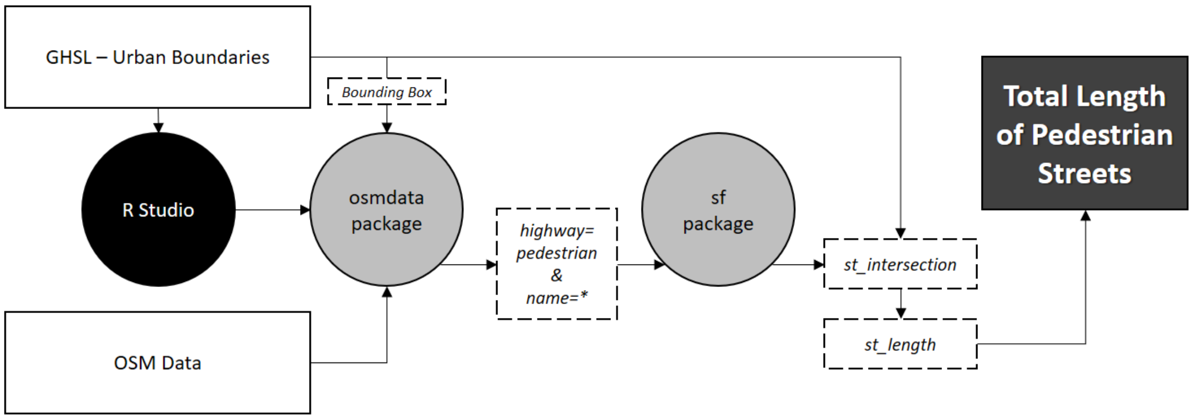


Figure 3. Correct usage of highway=footway for urban paths in Copenhagen, Denmark *(Source: overpass-turbo.com).*



In our analysis, we used for the calculation of the total length of pedestrian streets per city the *highway=pedestrian* and *name*=* OSM data, in which only pedestrian streets with valid address names are included. According to the OSM wiki page, the pedestrian tag is related to 'a road or an area mainly or exclusively for pedestrians in which some vehicle traffic may be authorized (e.g., emergency, taxi, delivery). Typically found in shopping areas, town centres, places with tourism attractions and recreation/civic areas, where wide expanses of hard surface are provided for pedestrians to walk' (https://wiki.openstreetmap.org/wiki/Tag:highway%3Dpedestrian, Accessed 22/7/2019). We decided to exclude from the measurement other pedestrian-related annotations, such as footway, path, steps, sidewalk, etc. because we observed extensive variability in the appropriate usage of these tags as well as different levels of data completeness in numerous cities. For example, Fig. 1 depicts the result of our *highway=footway* query in central Saint Petersburg, Russia, where the blue lines are missing the tag *footway=sidewalk*. On the contrary, Fig. 2 illustrates a proper example of the sidewalk tag attribution for footways in downtown Toronto, Canada. Fig. 3 displays the outcome of the *highway=footway* query in the vicinity of Frederiksberg gardens in Copenhagen, Denmark, where a correct application of the footway annotation is ascribed to urban paths. These examples allow us to conclude that the total length of footways is not comparable between different cities worldwide, as users do not fully submit the relevant details for different paths.

Figure 4. R workflow



2.2 GLOBAL HUMAN SETTLEMENT LAYER URBAN CENTRE DATABASE (GHS-UCD)

Heterogeneous administrative city boundaries are a common issue when comparing urban measures and benchmarking cities from different countries. Our analysis effectively addressed this issue, by using common geographies across cities. To do so, we employed the Global Human Settlement Layer and the Urban Centre Database (UCD), which is an open and free dataset, developed by the European Commission's Joint Research Centre and the Global Human Settlement Layer team. The UCD contains common urban boundaries for more than 10.000 global locations. These geographies were based on the combined EU and OECD definitions of cities in which the spatial extent of urban areas is outlined by 'contiguous grid cells of 1km^2 with a density of at least 1.500 inhabitants perkm^2 and a minimum population of 50.000' (Bartzokas-Tsiompras & Photis, 2019; Poelman & Dijkstra, 2015). The database is accessible online (https://ghsl.jrc.ec.europa.eu/ucdb2018Overview.php, Accessed: 20/07/19), and the various demographic, socio-economic, and environmental attributes of cities are included. Nevertheless, the current work only considered (992) cities with populations of more than 500.000 per urban centre.

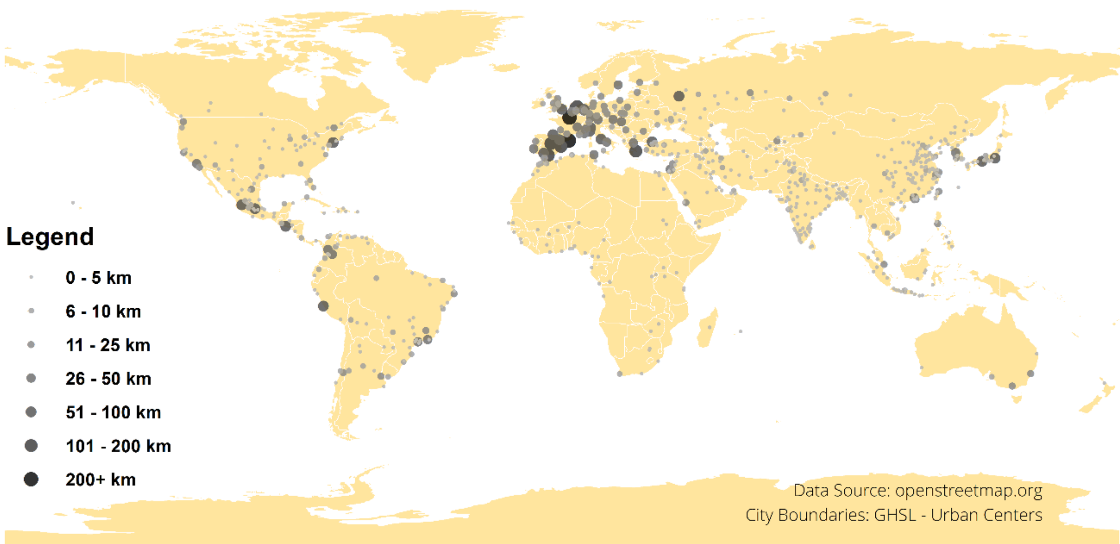
2.3 TECHNICAL PROCEDURES IN R

For calculations we used the *osmdata* and *sf* R packages in R Studio. The *osmdata* package downloads and uses OSM data based on overpass queries (*add_osm_feature*), and in turn, supports the quick and easy analysis of large VGI (*osmdata_sf*). Each query runs within a bounding box area (based on each city's boundary polygon). Next, we deployed the *sf* package in order to overlap (*st_intersection*) each query's result (OSM data in *sf* format) with the spatial extent of each boundary. Finally, the *st_length* function was used to calculate total length of pedestrian streets per each urban boundary (Fig. 4).

3. RESULTS

Data indicators of this research are available in an online repository (DOI:10.17632/fs9xxhh5yh.2) and some heatmaps of pedestrian streets in selected cities are presented in Fig. 9. As can be seen in Fig. 5, European cities are the champions of creating extensive networks of pedestrianized streets. The chasm between European urban areas and those of other continents is striking (figures 5 and 7). For instance, the median length in European metropolises is about 12.7km; the next median value is for Australia and New Zealand, with 5.5km (Fig. 8). On the other continents, the median ranges from 2.3km for Latin America/Caribbean to 1.2km for Asia. These findings highlight the differences in urban development patterns, and the different paths (compact vs. sprawling cities) followed to date in global urban transportation planning history (Newman & Kenworthy, 2015). Notably, from the top 20 cities in the total length indicator, 15 of them are in Europe, two cities are in North America and Asia, and three cities are located in Latin America/Caribbean. Only Paris and Barcelona exhibited extensive pedestrian networks of more than 200km, while 161 cities were found to have zero length. The majority of these 161 cities are in the developing countries in Asia (77%) and Africa (19%), and it is likely that the absolute zero values are due to the low coverage of OSM data in these regions.

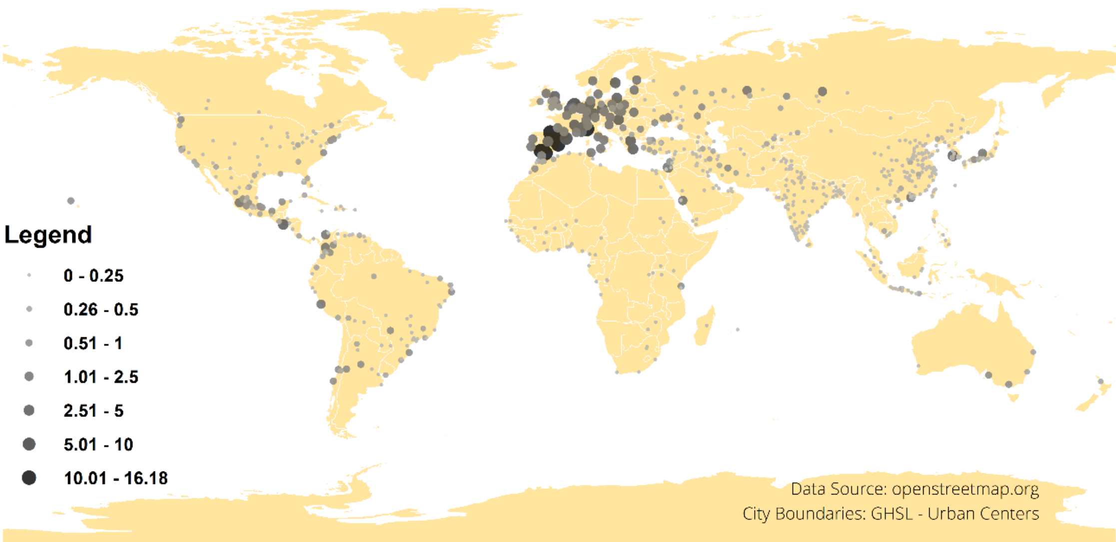
Figure 5. Total length (km) of pedestrian streets (OSM) per city (> 500.000 inhabitants).



In Europe, the highest pedestrian street lengths are located in Paris (223km) (see the map in Fig. 9), Barcelona (203km), Madrid (172km), Rotterdam (165km), and Valencia (140km). The majority of top-performing European cities are located in the Southern region, particularly Spain (seven of the top 15 European cities). It is interesting, though, to highlight that cities which often are characterized by a high quality of living and bold urban mobility policymaking, such as Copenhagen, Vienna, and Zurich, are not found among the top 15 European cities. In North America, the most pedestrian friendly are the largest cities, including New York

(91km) (see Fig. 9) and Los Angeles (50km), while all the other US or Canadian urban areas present values less than 22km. Remarkably, the highest ranked US city, New York, has pedestrian streets roughly 2.5 times smaller in length than the highest ranked European city, Paris. In Oceania, all metropolises demonstrate particularly low levels of pedestrianized street networks, in which the best-reviewed city, Melbourne, contains almost 19km of car-free roads. In Latin America and the Caribbean, the winners were Lima (93km), San Salvador (73km), Mexico City (67km), Guadalajara (57km), and Bogota (46km), while in Asia only three megacities excelled, namely Osaka (59km), Istanbul (57km), and Tokyo (57km) (see the map in Fig. 9). The remaining Asian cities possess networks lower than 32km (Seoul). As expected, African cities, exhibited the worst global performance. Only two areas have more than 10km of pedestrian street length: Tunis (30km) and Tangier (13km). Further, the majority of the highest values in Africa are concentrated in the Northern region, particularly Morocco (with five of the top ten African cities). Results were grouped according to five population groups (Fig. 7): XXL (more than ten million inhabitants), XL (five to ten million), L (between two and five million), M (between one and two million), S (500,000 to one million), so as to understand the role of the size of a city in our results.

Figure 6. Pedestrian street length (km) (OSM) per 100.000 inhabitants per city.



Finally, regarding pedestrian street lengths per 100.000 people rankings (Fig. 6), we see that Southern and Western European locales outclass cities from other world regions with the Spanish and Dutch generally receiving the highest scores. More specifically, most of the top positions for this indicator are occupied by relatively smaller European cities such as Genoa (16km), Zaragoza (15km), Malaga (13km), Bilbao (11km), Seville (11km), Valencia (10km), Amsterdam (10km) and Rotterdam (9km). For all other continents the highest values were: i) San Salvador city (4km) - Latin America, ii) Jeonju (3km) - Asia, iii) Tunis (1.5km) - Africa, iv) Adelaide (0.7km) - Oceania, and v) Bridgeport-Stamford area (0.8km) - North America.

Thus, the greater the population, the higher the median value of the indicator, meaning that larger cities tend on average to have more extensive networks of pedestrian zones (Fig. 7). Notably, in XXL cities (megacities), the best performing urban areas are New York, Mexico City, Osaka, Istanbul, and Tokyo. In the XL Group, the top five are Paris, Lima, London (80km), Bogota, and Rio de Janeiro (31km), while in top five L metropolises are Barcelona, Madrid, Athens (139km), Dortmund (83km), and Milan (62km). The M group of cities includes Rotterdam, Valencia, Amsterdam (112km), San Salvador (73km) and Budapest (49km). Finally, the S group's top five cities are Malaga (103km), Seville (93km), Bilbao (85km), and Zaragoza (77km), and Genova (88km).

Figure 7. Top 15 cities per continent (total length of pedestrian streets –km).

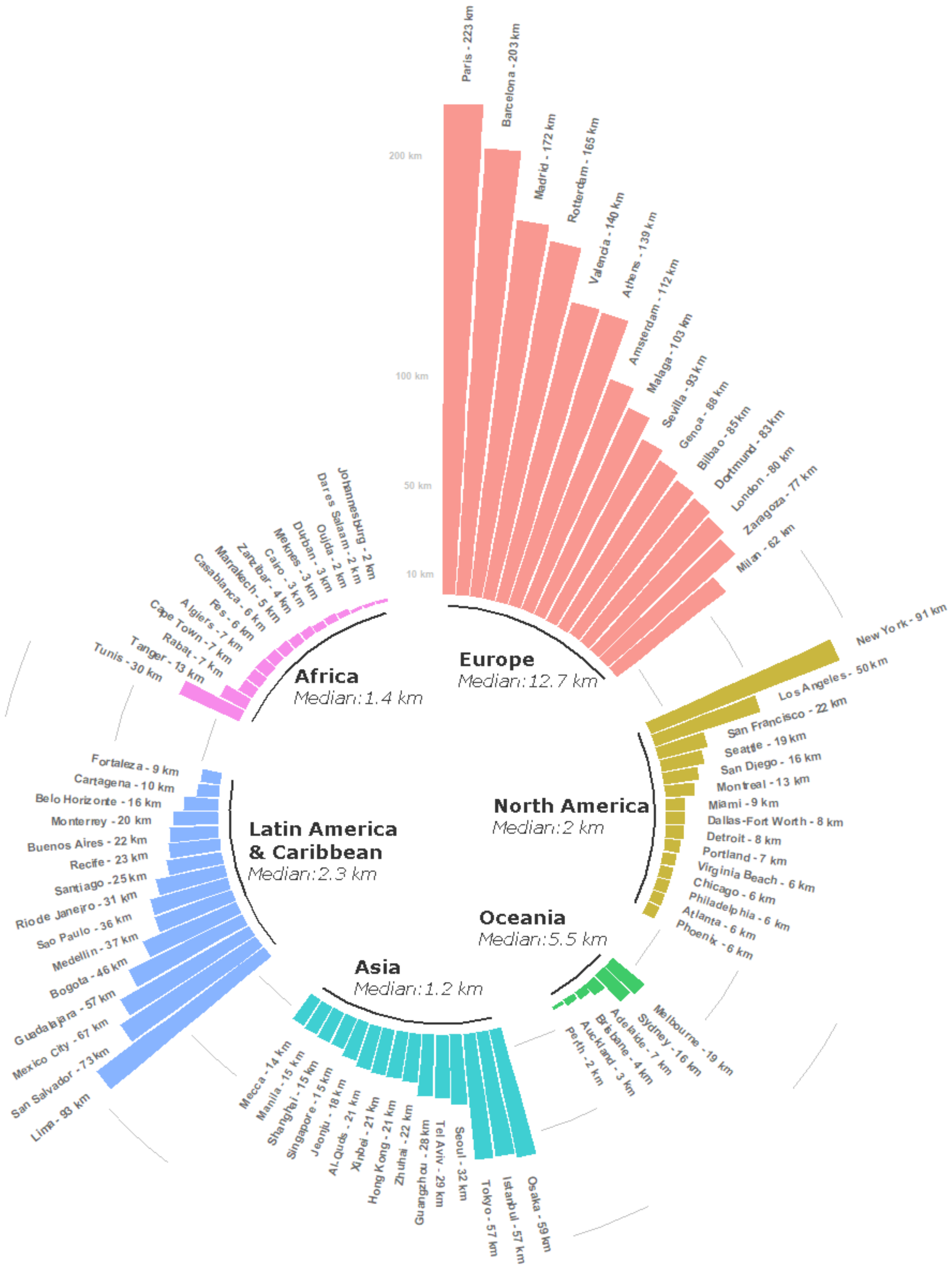
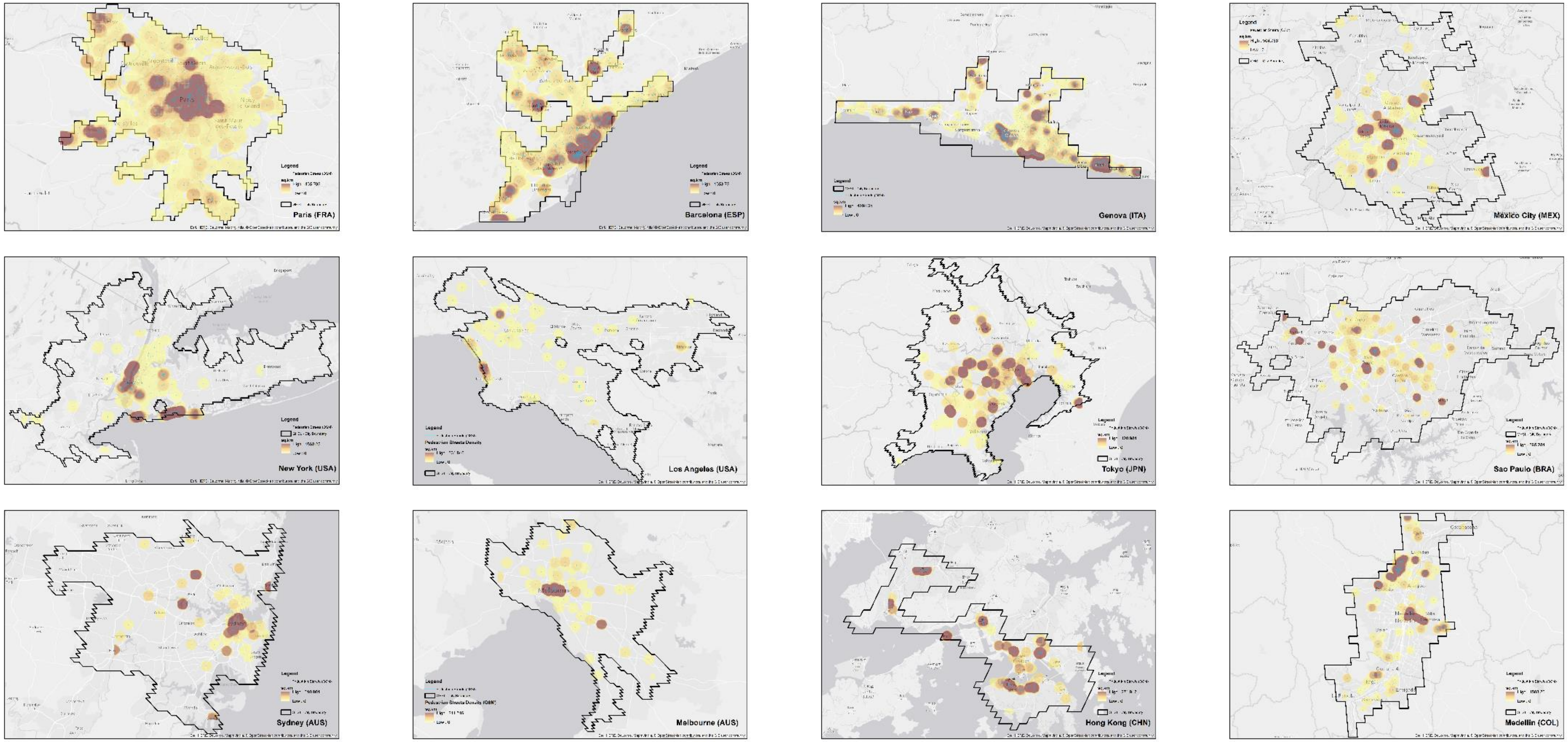


Figure 8. Top 15 cities per population size group (total length of pedestrian streets –km).

Figure 9. Heatmaps of pedestrian streets in selected cities



4. CONCLUSIONS

In this paper, in order to reveal differences in car-free strategies and concepts applied around the world we measured and compared the total length of pedestrian streets for 992 cities by utilizing open-source data and tools, such as OSM and R. Although OSM data are widely accepted in spatial, transport, and environmental studies (Barrington-Leigh & Millard-Ball, 2017), they suffer from certain limitations when applied to pedestrian mobility research, mostly due to quality and incompleteness issues (https://wiki.openstreetmap.org/wiki/Path_controversy, Accessed 22/7/2019). However, no other free global database currently exists to validate our findings. Thus, our indicators should be interpreted with caution, especially when related to less developed cities where the OSM data coverage is low (e.g., Africa).

Our results demonstrated that the majority of European urban areas have the most extensive networks of car-free streets in the world, as well as the highest ratios of car-free road networks per 100.000 people, globally. On the contrary, cities in North America and Oceania showed on average significantly smaller pedestrian street lengths compared to European metropolises. This is probably the result of their car-centric planning culture and urban sprawl, where the institution of extensive car bans, without adequate transit provision, seems rather impractical (Newman & Kenworthy, 2015). In many cities of the Global South, mainly in Africa and South/Central Asia, the pedestrian street is absent from urban and transport planning agendas. Nevertheless, some cities in less developed countries showed surprisingly significant pedestrian networks compared to their peers in the developed world. For example, Lima in Latin America has about eleven times more pedestrianized streets than Miami or Dallas in the US. Of course, this does not mean that Lima is in a better position in terms of urban sustainability than the US cities, nor should our results be interpreted as such. We argue that some of the most congested cities in the world, i.e. Mexico City, Lima, Istanbul, are included in the top global ranks of our study, which means that it is not enough for cities to partially implement car-free schemes. They must also actively promote city-wide measures for compact, mixed, and transit-oriented urban development (Bartzokas-Tsiompras & Photis, 2017, 2020b).

Future studies might investigate the association between pedestrian street length in cities and other economic or environmental urban phenomena (i.e. GDP, air pollution, congestion, etc.). With the rising rate of urbanization, examinations of the relationship between car-free development and sustainability issues could help cities to implement bold policymaking and create healthier and more inclusive places.

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DATA AVAILABILITY STATEMENT

Data indicators supporting reported results can be found online (Mendeley Data Repository) at DOI:10.17632/fs9xxhh5yh.2

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