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Abstract. Public transport plays a key role in expanding the distances that people can travel using active modes of transport. Studying walking accessibility to public transportation systems is highly relevant, since the walk to stops/stations can be particularly challenging for children, the elderly, citizens with disabilities, and for the general population during bad weather conditions or in pedestrian-unfriendly cities. This work presents a study on walking accessibility for the public transport system in Montevideo, Uruguay. The proposed methodology combines information of the bus stops and lines that operate in the city, the road infrastructure, and demographic information of the city to compute walking accessibility indicators to the public transport system. The results of the analysis suggest that over 95.5% of the population can access at least one stop when walking up to 400 m. However, these values are not evenly distributed among the population, with young citizens and men showing lower levels of coverage compared to their counterparts.

Keywords: Accessibility · Walking · Public transport

1 Introduction

The organization of transport systems condition the mobility of people, limiting their ability to participate in society and generating different forms of social exclusion [2]. In particular, geographic exclusion consists in the lack of automobility and access to public transport systems. The importance of ensuring mobility for non-automobile users to reach destinations beyond normal walking range is key for the mitigation of this type of exclusion.

Public transport systems complement the use of active modes of transport (e.g., walking, cycling) by extending their range. Thus, an increase in the use of public transport can deliver significant health benefits, as this mode almost

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always includes a stage with physical activity [14]. In particular, studying walking accessibility to public transport is relevant since the majority of users access networks in this manner. Passengers make their route choice based on the entire trip, including entering and exiting the public transport network [3], and tend to have an aversion towards long walks. However, passengers accept longer access and egress distances to/from the public transport network when the characteristics of the transport service (e.g., speed and frequency) improve [3]. Moreover, time is valued differently by passengers on each part of the trip. It is estimated that passengers value walking time up to 1.65 times more compared to in-vehicle time [1]. Therefore, a reduction in access times would render a greater reduction in the perceived total travel time for passengers.

This work presents a study on walking accessibility from a potential mobility approach using Montevideo, Uruguay, as a case study. The main objective is to provide accessibility indicators for Montevideo's public transport bus network that measure how easy/hard is for citizens in different parts of the city to access the public transport system by walking. For this purpose, several sources of information are combined, including bus lines, bus stops, road infrastructure and population distribution in the city. Through a geospatial analysis, three accessibility indicators are computed. The results obtained are inline with figures reported by the transit authorities while also allowing for a finer-grain analysis throughout the city.

The remainder of this article is organized as follows. First, Sect. 2 provides a review of relevant literature on the subject. Next, Sect. 3 presents the methodology to compute the accessibility indicators. Then, Sect. 4 presents the case study and discusses the results of the indicators. Finally, Sect. 5 summarises the main outcomes and potential lines of future work.

2 Related Work

Studies of walking as a mean of access to public transport networks are classified into two approaches: studies of observed mobility and studies of potential mobility. Observed mobility studies seek to accurately measure the distance or time walked by users to access a public transport network. Most related works with this approach are based on survey information, where passengers declare their point of origin and point of entry to the public transport network [4,5,13].

In contrast, the research reported in this article is categorized in the literature of potential mobility. One of the most widespread methods to capture the potential mobility of individuals is related to the concept of accessibility [6]. In general, accessibility indicators are based on identifying the number of opportunities that an individual has under certain cost parameters associated with the transited networks (e.g., time, distance). Studying walking accessibility to public transport networks implies considering each stop in the system as an opportunity and walking through the road infrastructure as the access method. The standard procedure consists in evaluating the coverage of the transport network through the proportion of the population that is able to access the network by walking up to a certain distance threshold.

An interesting approach was proposed by Langford et. al, which studied the accessibility to the public transport system of South Wales, UK [10]. The authors introduced an accessibility measure based on enhanced *floating catchment* techniques, which capture many detailed aspects of accessibility. The method is a particular case of a gravitational model used to measure spatial interaction. Using information about public transport schedules and stop locations, the authors calculated a walking accessibility indicator to the transport system through geospatial analysis tools. The proposed indicator incorporates aspects of proximity, frequency, demand and availability of the public transport service. The authors concluded that their approach provides considerably more analytical detail than traditional approaches based on calculating the percentage of population covered using Euclidean buffers and area-ratio overlays.

When calculating the distance people walk to access public transport, several approaches exist in the literature to measure the distance from the point of origin to the point of entry to the transport system. The standard procedure in most recent works seems to be to use the shortest distance traveled through the road network from origin to the stop/station of entry [4,5,13]. Many guidelines in the literature suggest using a threshold distance of 400 m [4,13]. However, the origin of this value is unclear; although it might be related to the work of Neilson and Fowler [4]. Several works have shown that this assumption is quite realistic on average. A study done in The Hague, Netherlands, suggests that the median distance walked as a feeding method for the public transport system is 380 m [13]. Similarly, for Sydney, Australia, the median walking distance was estimated to be 364 m for the bus system [4]. Nevertheless, both works highlight that these median values indicate that exactly half of the respondents travel beyond the 400 m threshold used as a rule of thumb.

For the specific case study used in this work—Montevideo, Uruguay—there are no prior studies on walking accessibility to public transport to the best of our knowledge. Some previous works have addressed accessibility to employment opportunities [8], to hospitals [9] and to education centers [7] using public transport, but were not focused on the access/egress to the public transport network. Also, a household mobility survey was conducted in 2016 to obtain a large-scale image of the mobility in the city, considering all modes of transportation and incorporating the metropolitan area of the city [11]. In this survey, participants were asked to provide rough estimates of their walk to stops for those trips involving public transport. Lastly, some figures have been suggested by the transport authorities in the press stating that nearly 97% of Montevideo's population is covered by the public transport network when considering a walking threshold of 400 m [12]. These figures confirm that Montevideo's city planners also assume a fixed distance of 400 m—as guidelines in the literature suggest—and provide a reference accessibility value for comparison.

3 Methodology

This section describes the methodology applied to calculate the indicators of walking accessibility to public transport systems. The workflow is based upon the reviewed literature albeit slightly adapted to the specific case study addressed in this work.

The following data sets are needed to compute the walking accessibility to public transport indicators:

- Zoning of the studied area
- Road network of the studied area
- Population of each zone
- Geographical location of stops
- List of public transport lines that operate on each stop

Indicators are based on a service area (sa) geospatial analysis. This method consists in delimiting the portion of the road network (RN) from which the stop can be reached within a fixed walking distance threshold (d). An example of service area calculation is shown in Fig. 1. The road network is displayed in grey, the stop is marked with a blue dot, and an example service area for the stop is defined in orange. Since bus stops are located in the sidewalk, it is necessary to first project them to the nearest point in the road network.

For notation purposes we will define the service area for a bus stop s_i, given the road network RN and a threshold walking distance d as:

$$SA_i = sa(s_i, RN, d) \tag{1}$$

As outlined in the review of related works, there seems to be a consensus among city planners of using $d = 400\,\text{m}$ as the walking distance threshold to access public transport networks.

Then, to calculate accessibility indicators in an aggregated way, a zoning of the area of study must be provided. Depending on the nature of the analysis, coarser or finer zonifications may be considered. Since the road network itself can be used as the delimitation of the zones, it is advisable to take a small buffer for each zone in order to consider roads right in the edge of the zone. Figure 2 shows an example of a zone that correspond to a block; the buffer plotted in orange allows considering the portion of road that delimits the zone within it. Without this buffer, no portion of the road network would be considered to be inside the zone.

Given a pre-defined set of zones $z_1, z_2, ..., z_n$, the portion of the road network within each zone is considered as $rn_1, rn_2, ..., rn_n$. Thus, a formulation is given in Eq. 2, where $\cap$ is the geospatial intersection operation and $b(z_j, B)$ is the resulting polygon of applying a geospatial buffer operation of B units to zone z_j.

$$rn_j = RN \cap b(z_j, B) \tag{2}$$

Thus, with the previous formulations, the definition of whether a stop s_i covers a zone z_j can be defined:

$$s_i \text{ covers } z_j \iff rn_j \cap SA_i \neq \emptyset \tag{3}$$

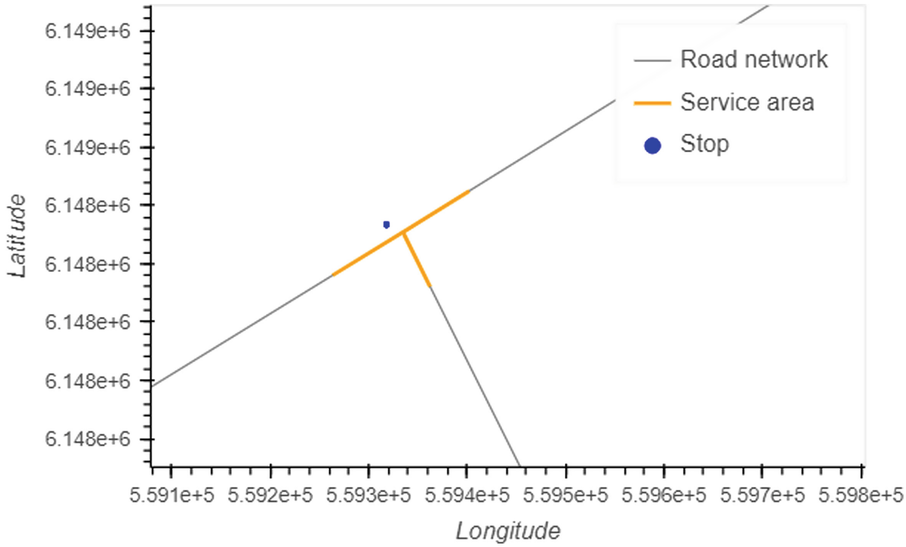

Fig. 1. Service area analysis example

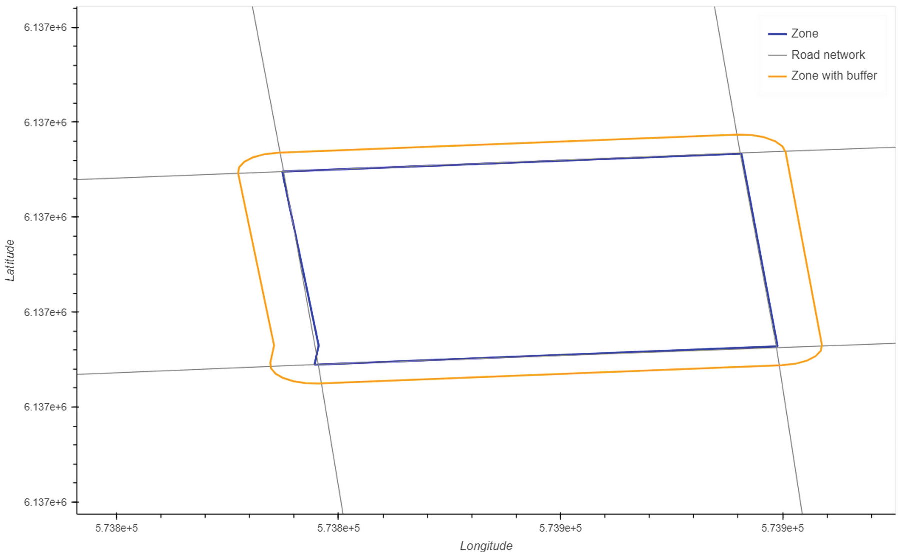

Fig. 2. Zone with buffer example

Also, given the aforementioned road network portions and the service area of each stop, the overlap between these can be computed to determine the coverage c_j at the zone level:

$$c_j = (SA_1 \cup SA_2 \cup ... \cup SA_n) \cap rn_j \tag{4}$$

Summarizing, three accessibility indicators at the zone level are defined:

1. **Number of bus stops covering each zone at d $\leq$ 400 m:** corresponding to the number of bus stops that comply with Eq. 3
2. **Number of bus lines covering each zone at d $\leq$ 400 m:** calculated as the count of different bus lines that operate on bus stops that comply with Eq. 3
3. **Percentage of population within the zone covered by at least one bus stop at d $\leq$ 400 m:** assuming a uniform spatial distribution of the population in the road segments of each zone, coverage can be estimated through Eq. 4

4 Case Study: Montevideo, Uruguay

This section presents the results of the analysis of walking accessibility to the public transport network in Montevideo, Uruguay.

4.1 City and Public Transport System Overview

Montevideo is the capital and most populated city of Uruguay. It is situated on the southern coast of the country. It has a population of 1,3 million, which constitutes 40% of Uruguay's total population. The size of Montevideo is 201 km^2 and therefore, has roughly 6.5 thousand inhabitants per km^2. It is a sparsely populated urban area compared to other large cities in Latin American.

The Statistics National Institute (INE) has divided the Uruguayan territory for statistical purposes. Three levels of division are considered:

- Section: Montevideo is divided into 27 Sections, according to the limits established in the 1963 Census. Sections are shown in Fig. 3 with dark blue lines.
- Segment: each Section is subdivided into Segments, which consist of a set of blocks. Montevideo is comprised of 1 063 Segments, which are marked in blue in Fig. 3.
- Zone: is the smallest identifiable zoning defined by INE. Each Segment is divided into several Zones. In densely populated parts of the city Zones usually coincide with a single block. In more rural areas, Zones correspond to portions of territory defined by natural or artificial limits (e.g., watercourses, highways, local roads, railways). Figure 3 shows the 13 608 Zones of Montevideo in sky blue.

In this work Zones are used to compute the walking accessibility indicators, which are the finer-grain zoning division available for the city.

The public transport system in Montevideo is based on buses. Public transport plays an important role in the city. Results from the Mobility Survey of the Metropolitan Area of Montevideo 2016 show that bus trips represent 25% of all trips [11]. Figure 4 outlines the road network, bus lines and bus stops of Montevideo. It is easy to distinguish the central parts of the city as the density of bus stops increases and most lines converge to it.

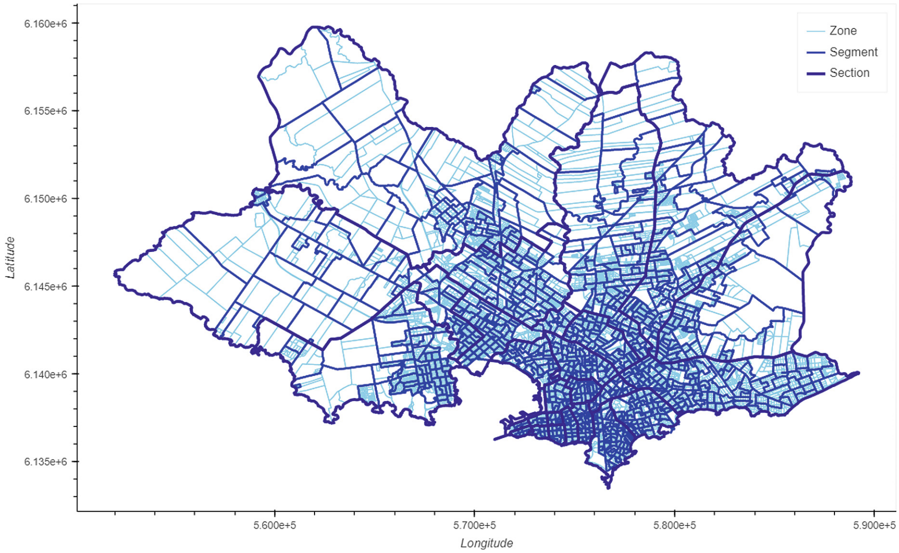

Fig. 3. Division of Montevideo in sections, segments, and zones.

4.2 Software and Tools

Service area analysis was made with QGIS through its algorithm provider using the function *service area*. Similarly, the buffer of Zones was carried out using the vector spatial analysis tool of QGIS. On the other hand, the computation of the accessibility indicators were made through Jupyter Notebooks, which offer a programming ecosystem that integrates data, code and results. Geospatial information was handled through the *Pandas* and *Geopandas* libraries and visualizations were created using the *Bokeh* library.

4.3 Data Sources and Data Cleansing

The main data sources were obtained through the open data catalog of the Municipality of Montevideo. All data sets obtained from this source were downloaded on 3/18/2022. The datasets used correspond to the bus lines and bus stops of the public transport system, the road network of Montevideo, and the population data from the 2011 census for the three existing zoning levels: Section, Segment and Zone.

Bus Stops and Bus Lines. Cleaning the bus lines and stops data comprised a series of consistency checks. A first approach with the data was enough to rule out a line that is active only during the Carnival season in Montevideo and was therefore removed from the lines and stops data set. Another verification carried out was through a full join between the data set of lines and the data set of stops, to check that all lines have associated stops and that all stops have

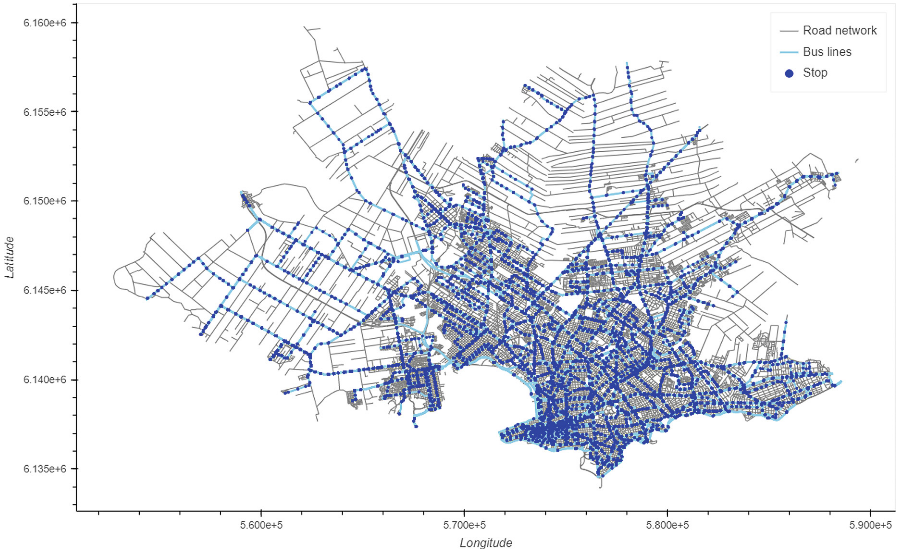

Fig. 4. Montevideo: road network and public transport system

at least one corresponding bus line. As a result of this analysis, one line was removed because it did not have corresponding stops in the set of bus stops. Finally, all the bus stops that were located outside of Montevideo were removed and the lines that operate beyond the department were cut short. In conclusion, the remaining data set of bus lines has 634 different lines; and the set of bus stops is comprised of a total of 4 643 unique stops.

Montevideo Road Network. The cleansing process of the Montevideo road network consisted simply in correcting invalid geometry errors using the predefined Check Validity function provided by the QGIS topology checker plugin.

4.4 Accessibility Indicators

The three accessibility indicators were computed according to the methodology, using the finest zoning available for the city, and considering a buffer of 10 m for each Zone as described in the methodology.

The first indicator shows the number of bus stops that cover each Zone considering a walking distance of 400 m or less. Results are shown in the map of Fig. 5, where darker shades of blue indicate a higher number of bus stops reachable from the Zone. The city center (south central area in the map) can be easily distinguished given the higher density of bus stops. Some peripheral Zones also stand out, since Zones in the periphery are larger in area and thus may have access to a higher absolute number of bus stops.

The mean number of bus stops accessible by a given Zone is 9.2; whereas the median is 9.0. A histogram of the distribution of the number of bus stops

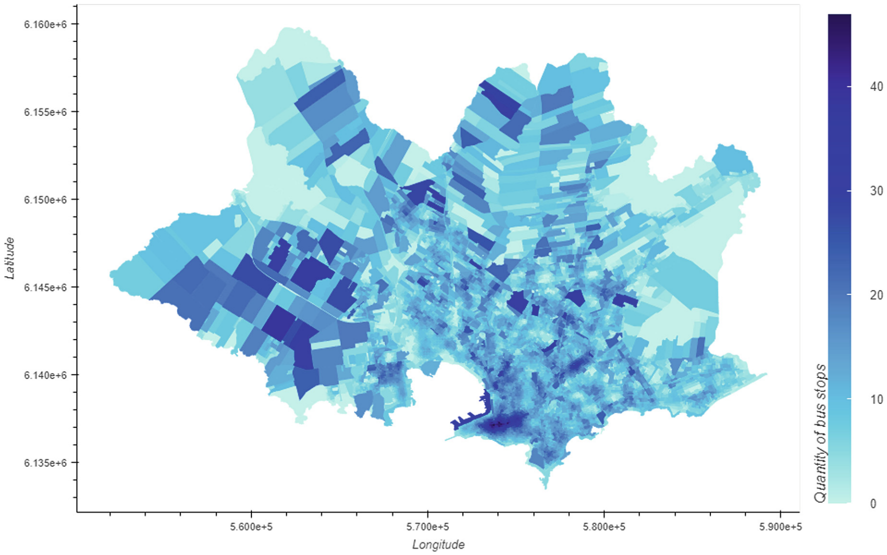

Fig. 5. Number of bus stops accessible when walking up to 400 m per Zone (Color figure online)

is presented in Fig. 6. The *saw-tooth* shape of the distribution can be explained by the fact that bus stops tend to be placed on each side of the road to service both directions of bus lines. Thus, it is more likely to reach an even number of bus stops (i.e., for inbound and outbound bus lines).

Next, we calculate the second accessibility indicator, i.e., the number of bus lines that are accessible for each Zone when considering a walk of 400 m or less. Results are shown in the choropleth map in Fig. 7, where darker colors indicate that a larger number of lines are accessible for that Zone.

The city center in this map stands out compared to other areas since many different bus lines converge to it. Also, the main arteries of the city (going East and North from the city center) can be distinguished because of the density of bus lines that operate over those main roads. Moreover, comparing Fig. 5 with Fig. 7, a softening of peripheral areas can be appreciated, suggesting that while some Zones in the periphery access a large number of stops, these stops provide service to a small number of bus lines. The mean number of lines is 16.7 and the median is 10.0. The distribution of the number of bus lines accessible is shown in the histogram in Fig. 8.

The third and last accessibility indicator illustrates the percentage of population of each Zone covered by the union of service areas. Results are shown in Fig. 9. Key results are that the mean coverage is 94.1% and the median is 100%. An histogram of the distribution of coverage is shown in Fig. 10 and shows that, for most Zones, 100% of their population have access to a bus stop walking 400 m or less. Given the assumption that the population is evenly distributed

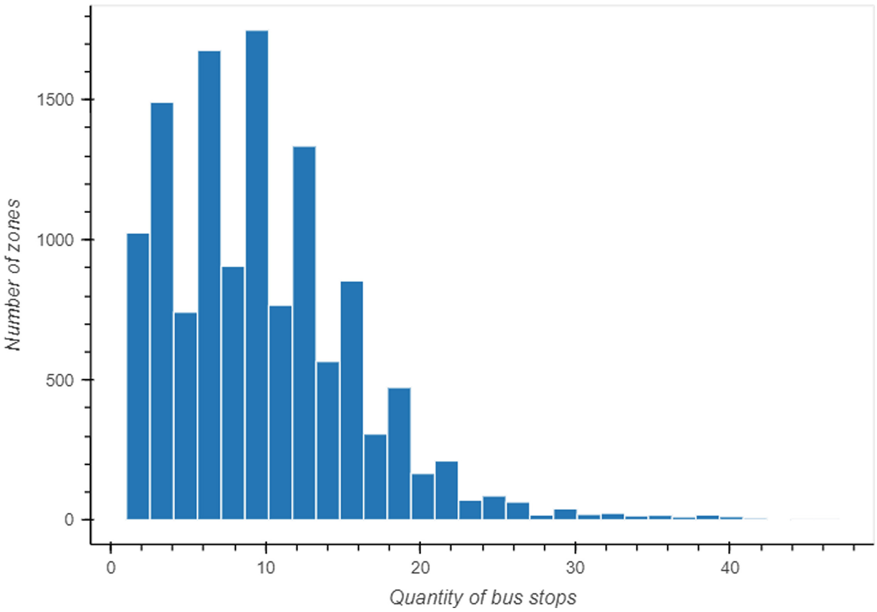

Fig. 6. Distribution of the number of bus stops accessible when walking up to 400 m

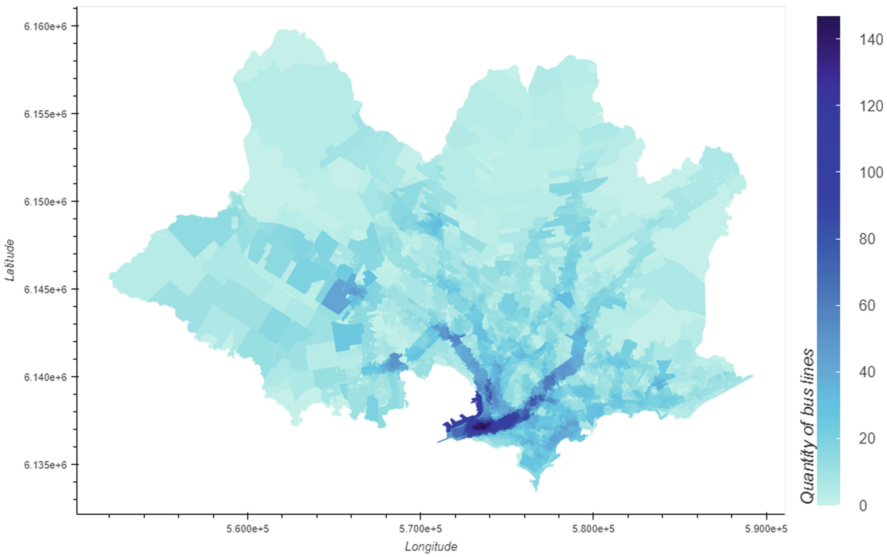

Fig. 7. Number of bus lines accessible when walking up to 400 m per Zone

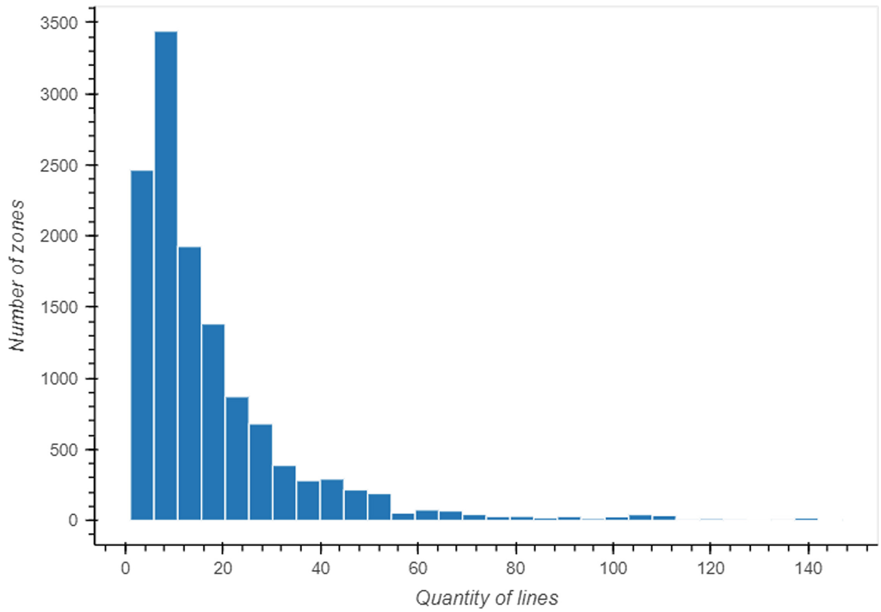

Fig. 8. Distribution of bus lines accessible when walking up to 400 m

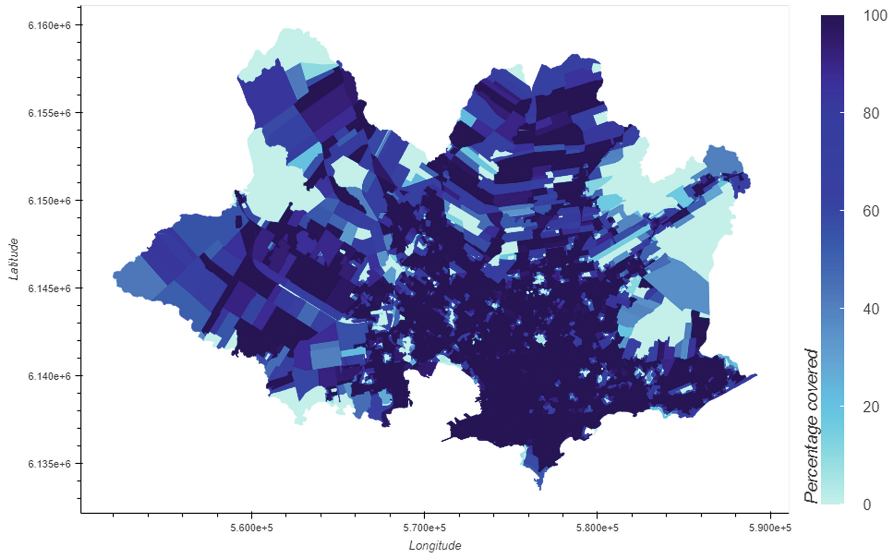

Fig. 9. % of population with access to a bus stop when walking up to 400 m per Zone

on the road network, the percentage of Montevideo's population covered by at least one bus stop at 400 m or less is 95,5%. When considering the population split by gender, women (95.7%) present a slightly higher percentage of coverage

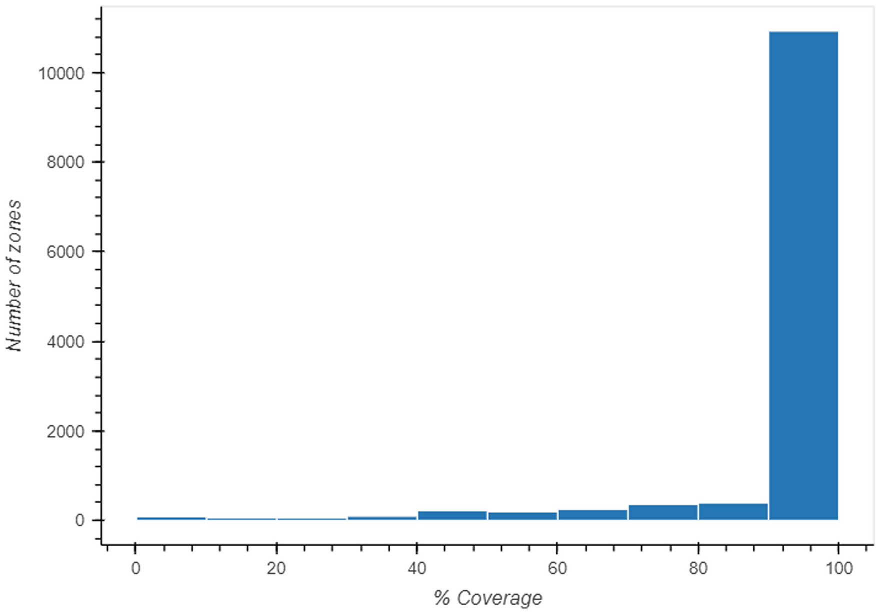

Fig. 10. Distribution of the % of population with access to a bus stop when walking up to 400 m

than men (95.3%). In regards to age, young citizens (0 to 14 years old) present the lowest levels of accessibility with a coverage of 93.9% whereas senior citizens present the best values of accessibility with 95.6%.

5 Conclusions and Future Work

This work presented a study on walking accessibility to public transport systems using Montevideo, Uruguay, as a case study. As public transport in Montevideo is based on buses, the main data sets considered are bus stops and lines. The analysis was performed using the smallest zoning available for the city which is roughly equivalent to blocks in densely populated areas of the city. Through a service area analysis using geospatial tools we estimated the coverage of Montevideo's public transport bus network. The implemented methodology accounts for the actual walk that passenger do through the road network, improving other simpler estimations based on straight line distances and buffer areas.

The main finding of the analysis is that 95,5% of Montevideo's population can access at least one bus stop when walking up to 400 m. However, when considering the number of different bus lines that operate on these stops, results show that areas in the outskirts of the city have access to fewer bus lines compared to downtown areas. The results are in-line with figures reported by transport authorities in the press (around 97% of coverage). The overestimation in coverage can be explained by the simpler approach used by the authorities (i.e., straight line buffer areas) compared to the more precise approach proposed in this work based on service areas. Additionally, results showed that the walking accessibility is unequal when considering gender and age, with young citizens (0 to 14 years old) and men showing lower levels of coverage compared to their counterparts.

The main lines of future work include incorporating line schedules in order to analyze how accessibility indicators and coverage vary throughout the day. Also, we propose to compare the computed indicators against the results from a household mobility survey conducted in 2016. Finally, the results of this study could be used as input to address many different optimization problems, such as, bus stop (re)location, network redesign, and expanding the catchment areas of current bus stops by including facilities for other active modes (e.g., shared bikes) to be used as a feeding method for the public transport system.

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