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Accessibility to opportunities based on public transport gps-monitored data: The case of Santiago, Chile

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ABSTRACT

We study buses' accessibility to education, health, and job opportunities in Santiago, Chile. Our approach computes travel times during a week using full real-world GPS data for the 6681 buses of the public transport system. The use of such disaggregated data allows us to calculate accessibility based on real operating conditions rather than planned schedules, as most previous contributions do. To develop our analysis, we divide the city into 1390 walkable zones, and we compute travel times between them. Then, we calculate the number of opportunities reachable from each zone to the rest of the zones, and we aggregate them at a municipality level. Our main finding is that public transport is not able to alleviate the inequality given by the geographical distribution of opportunities in the city. We also find that accessibility for public opportunities is quite more homogenous throughout the city compared to private opportunities. The center and north-east part of the city, where the wealthier municipalities locate, attain the highest levels of accessibility to jobs and private health institutions. The west part of the city shows worrying poor accessibility to complex hospitals, while the south part is excluded from job opportunities. Overall, policies should aim to mitigate these inequalities by improving the quality of public transport services. Conventional alternatives include increasing bus service frequency and expanding the dedicated infrastructure for public transport. In the long term, better city planning is required to facilitate spreading the opportunities all over the city.

1. Introduction

Cities' development and the corresponding urban land use shape the playground for accessibility. Indeed, the quantity and spatial distribution of activities within a city is a crucial factor when determining the number of people that can access to opportunities. However, there is also a strong relationship between accessibility and the public transport system. Accessibility improvement can be achieved by increasing the number of urban opportunities, but also by enhancing the performance of public transit, making farther opportunities reachable.

The lack of appropriate transport accessibility might deepen social segregation and might result in a mismatch between social groups and social benefits (Blumenberg and Shiki, 2003). For instance, worse job accessibility translates to a lower probability for individuals to be employed (Hu, 2017). Equity can be measured through the accessibility that a city gives to people. The higher the accessibility to essential opportunities (education, work, and health) the city provides, the more equitable it is. Conversely, if the city presents vast inequities concerning both the distribution of essential goods and the connectivity delivered by the transportation network, then the inhabitants of different locations should experience dissimilar social benefits and costs. In this sense, our research question is: does the Santiago transport system provide equitable access to opportunities?

Besides locations, accessibility indicators should consider time as a critical element. Villar et al. (2011) claims that "time is a unique good that should be given maximum value and that its correct use depends largely on the quality of life and happiness of people, as well as productivity and competitiveness as a country." Thus, shorter travel times translate into well-being and development of life in society, and any reduction implies an increase in social welfare. Time is a vital component of accessibility that can measure the ease with which opportunities are accessed in a specific place, given a transport network (Niemeier, 1997).

Due to the need for improving the transport system quality continuously, several world's capitals have incorporated operational and

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quality indicators, being Singapore and London two representative cases. These transport systems have improved under the regulation of contracts, which require compliance with regularity, frequency, and place-time-route indicators. Santiago transport system has not been exempted from the need to create and enforce indicators (Beltrán et al., 2013; Frez et al., 2019), which have suffered multiple changes since the launch of the current public transport system, Transantiago, in 2007. Nevertheless, none of these indicators have included accessibility to opportunities, which may have a sizable impact on the efficiency of public transport.

Literature provides several ways to define the accessibility concept. For instance, Hansen (1959) defines accessibility as "the potential of opportunities for interaction," while Koenig (1980) denotes accessibility as "the ease with which any land-use activity can be reached from a location, using a particular transport system." Hernández (2017) defines accessibility as "the result of the interaction between individual factors, the transport system and the urban form or land-use." According to Boisjoly et al. (2020), accessibility can be broadly understood as the level of access to opportunities. In this paper, we follow the latter approach, understanding accessibility as the outcome of the interaction between the distribution of essential opportunities within the city, and the performance of the public transport system. Thus, we consider a measure of accessibility computed as the number of opportunities (work, education, and healthcare) reached within a fixed amount of time.

The objective of this paper is to analyze the accessibility to opportunities in Santiago city by public transit. Unlike previous works, in this research, we examine at the microscopic level the events that occur in different locations using public transport GPS-monitored data. To the best of our knowledge, this is the first paper that evaluates accessibility to opportunities using real operational data rather than planned schedules. As transit is subject to the schedule-based fluctuations in the provision of service, incorporating real spatiotemporal data into the accessibility measures computation should increase their validity (Farber and Fu, 2017). To do so, we divide the city into walkable zones, and we compute travel times between them. Then, we calculate the number of opportunities reachable from each zone, and we aggregate them at a municipality level. We analyze these results from different perspectives, such as spatial and social equity, providing public policy insights.

The rest of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the case study of this paper. Section 4 describes the data. The proposed methodology is discussed in Section 5, whereas, Section 6 discusses the computational experiments. Finally, Section 7 provides some concluding remarks and directions for future research.

2. Literature review

2.1. Accessibility measures

There are several ways to measure accessibility, which are used for different purposes. Geurs and Van Wee (2004) proposes a framework of four relevant components of accessibility to opportunities within a city, namely, land use, transportation, temporal, and individual. The change in any of these components has an impact that goes beyond its static influence since it also induces changes over the rest of the components (e.g., a change in urban land use may induce a change in travel patterns, thus influencing the transportation component). Using this framework, the authors then review different accessibility measures used in the literature.

Hansen (1959) is known as one of the pioneers in formalizing accessibility indicators. The author defines a relative measure of the accessibility at zone 1 to an activity located within zone 2 by Eq. (1).

$$A_{1-2} = \frac{S_2}{T_{1-2}^{x}} \tag{1}$$

where S_2 is equals to the size of the activity in zone 2 (e.g., number of jobs), T_{1-2}^{x} corresponds to the travel time or distance between zones 1 and 2, and x is an exponent that must be adjusted. The author applies this indicator to the Washington metropolitan area for three different activities, namely, employment, shopping, and residential.

Ingram (1971) proposes an accessibility classification, where they distinguish between *relative accessibility* and *integral accessibility* indicators. The main difference between these two concepts is that relative accessibility refers to the degree of connection between any two points. In contrast, integral accessibility relates to the degree of interconnection between a specific point, and all others within a spatial set. The integral accessibility $A_i$relates to the relative accessibilities a_{ij}, as shown in Eq. (2).

$$A_i = \sum_j a_{ij} \tag{2}$$

The indicator proposed in our paper can be considered as an integral accessibility indicator. The same concept is named *contour measure* by Geurs & Van Wee (2004) because it counts the number of opportunities that can be reached within a given travel time. A general contour measure is given by Eq. (3).

$$A_i = \frac{\sum_j O_j \bullet f(t_{ij})}{\sum_j O_j} \tag{3}$$

where A_i is the accessibility of zone i; O_j is a measure of activity in zone j; t_{ij} is the travel time between zones i and j; and $f(t_{ij})$ is a measure of travel impedance between zones i and j.

Koenig (1980) proposes the indicator given by Eq. (4) to measure accessibility.

$$A_{ik} = \frac{\sum_j S_j^k e^{-x^k c_{ij}^k}}{\sum_j S_j^k} \tag{4}$$

where S_j^k is the potential number of destinations reached by individual k in zone j; x^k is a calibration parameter for individual k; and c_{ij}^k is the generalized transport cost for individual k between zones i and j. This type of indicator is called *potential accessibility measures* in Geurs & Van Wee (2004). Opposed to Koenig (1980), in this paper, we do not analyze the accessibility at an individual level but at the microzone level.

2.2. Case studies

In the USA, Allen et al. (1993) defines an accessibility index E that captures the overall transportation access level of a region, defined as the average travel time between two random points in that area. According to Ingram (1971) classification, index E corresponds to a relative accessibility measure. The authors apply the proposed methodology to Philadelphia, USA, finding that $E \approx 40$ minutes. The authors also discuss the relationship between this accessibility index and employment growth rate, finding that a decrease in the former produces a significant increase in the latter. Horner and Mefford (2005) studies accessibility to jobs in Texas, USA, using geographic information systems (GIS) to facilitate accurate estimates of the bus travel times between residences and workplaces. Wang and Chen (2015) computes an integral accessibility measure in Ohio, USA, differentiated by travel modes with different time buffers for each one. Then, using ordinary regression models, the authors study the impact of external factors in the accessibility of a zone, finding that, for example, race and educational level may have a sizable effect over accessibility to job opportunities.

In Europe, Vandenbulcke et al. (2009) compares the spatial structure of car accessibility to towns and railway stations during peak and off-peak hours in Belgium for the country's 2616 municipalities. They use network data gathered from three regional Ministries to build an undirected graph to assess the impact of congestion on accessibility inequalities. Opposed to our case, travel times are estimated using an impedance function, which quantifies the time needed to cross urbanized areas. Thus, no real travel time data is used. Reggiani et al. (2011) investigates spatial accessibility patterns in Germany while comparing the results with a previous study from 2002. The authors use a city network approach to analyze labor accessibility using employment history statistics in 17 districts all over the country.

In Asia, Wang et al. (2015) computes flow-based accessibility measures using the place rank approach and smart card data in Singapore. The proposed method is an alternative to traditional methods that usually use travel time information in the system. Hu et al. (2017) uses an integral measure of accessibility to jobs in Beijing, China. The authors study how the change in the total amount of job supply and demand affects different groups, finding that between 2000 and 2010, the socio-economic transformation reduced job accessibility, especially for the high-educated population. Liu and Zhang (2018) provides a benchmark analysis of high-speed rail impacts on accessibility in city-cluster regions of China using a gravity model. They show that accessibility increases in all cities and regions during the studied period. Particularly, access disparity within most city-cluster regions decreases, whereas the between-region gaps remain during the study period of analysis.

In South America, Quirós and Mehndiratta (2015) analyzes the relationship between accessibility and growth patterns in Buenos Aires, Argentina. Using the road network and transit patterns, the authors conclude that the city of Buenos Aires has grown inefficiently, with low-density patterns in the periphery that have limited transit accessibility to employment opportunities when compared with the accessibility offered by automobiles. Hernández (2017) uses an integral accessibility measure in Montevideo, Uruguay, to conclude that there exists inequality in terms of the capacity to reach two types of urban opportunities: education and jobs. Even though the case we present in this paper follows a similar approach, we improve the application by using real travel times between zones. Carneiro et al. (2019) use the same methodology proposed by Hernández (2017) with data gathered from Google Maps to study accessibility to job opportunities in Rio de Janeiro, Brazil. The results show an unequal distribution of accessibility, in which the farthest regions from the urban center have less accessibility due to the high concentration of jobs in the city center. Recently, Boisjoly et al. (2020) computes a cumulative accessibility indicator in Sao Paulo, Brazil, finding a clear trend of inequitable public transport provision in all four metropolitan regions.

In Chile, Rojas et al. (2016) computes accessibility to urban green spaces in two medium-size cities using a cumulative opportunities measure. The authors show that, for these two cities, variations in accessibility tend to be driven by age and gender, and less by income. Martínez et al. (2018) analyzes the relationships between public transport and social housing policy in deprived areas of Santiago. As we do, the authors analyze accessibility, yet, we can identify two main differences. First, the authors focus on zones where social housing has been developed while we analyze the whole region. Second, the authors use planned schedules rather than GPS data as we do. The main conclusion of the study is that housing policies put people at a disadvantage by increasing the distance between them and the opportunities of the city, while public transport fails to mitigate these distances, increasing the patterns of segregation. Rojas et al. (2019) studies accessibility to basic opportunities (education, health, and retails) in Los Angeles, Chile. Using data gathered from a mobility survey done in 2004, the authors use an integral accessibility measure differentiated by travel mode. The results show a sharp spatial difference in the accessibility levels, with the city center concentrating the highest number of opportunities.

The use of GPS data has been scarce for determining accessibility in cities. However, there are some exceptions. Escobar and Garcia (2012) analyzes territorial accessibility through travel times' estimations using GPS data for different types of vehicles in Manizales, Colombia. The authors conclude that taxis provide better accessibility than any other transport mode. Particularly, they show that urban public transport provides the worst global accessibility media conditions. Kalaanidhi and Gunasekaran (2013) computes accessibility indexes from a single route in Chennai City, India. The authors use GPS data to obtain travel time between OD points and then use the accessibility indexes to estimate bus ridership. Cui et al. (2016) uses taxi GPS data to find problems in the road network accessibility. The authors applied the proposed approach in Harbin, China, finding 20 regions that have the lowest level of accessibility by car among all the identified residential areas. A particular issue is found with petrol stations because 92.6% of the residential areas have to travel longer than 30 min to refill their fuel tanks.

Overall, to the best of our knowledge, this is the first paper that uses full real-world GPS data to compute accessibility indicators to opportunities using public transit.

3. The case of Santiago, Chile

The Metropolitan Region is the most populated territorial unit of Chile. It has 7.1 million inhabitants living in 2.3 million households. Although its large population size, the Metropolitan Region is the second smallest administrative region by land area. Particularly, it spans 15,403 km^2 encompassing only 2% of the national territory. Santiago, the capital city of Chile, is located within this region. The Metropolitan area of Santiago covers 37 municipalities, which are independent administrative units (Fig. 1).

Land area (Fig. 1) and average income (Fig. 2) vary significantly among municipalities, as a result of several social changes. In fact, Santiago has undergone several expansion processes, including large population displacements between central and peripheral municipalities, which has removed the most impoverished populations from urban centers. These changes have increased social segregation (Álvarez and Cavieres, 2016), deepened by an agglomeration of wealthy people in Providencia, Vitacura, and Las Condes. Social housing policies have been one of the main reasons for this phenomenon (Ducci, 1997). Additionally, there has been a displacement of the urban economic center from the historical one to the north-east sector (Ducci, 2000).

Nowadays, most of the trips from peripheral municipalities to the urban economic center use public transport. Santiago transport system, Transantiago, is based on a private–public operation where the Chilean state bids routes to private operators. Transantiago includes three types of transport modes, namely Metro, buses, and interurban trains, covering a total of 680 km2 and 34 municipalities. Metro has a network length of 140 km, six lines, and 136 stations spread over 26 municipalities. The Alameda-Nos interurban train has a rail length of 20 km and ten stations. Interurban trains connect Metro stations with several remote municipalities, such as San Bernardo, Lo Espejo, and Pedro Aguirre Cerda. The bus system has 6681 buses, 11261 stops, and a road network length of 2834 km. Transantiago has an integrated tariff system since 2007; that is, the payment in one mode allows using other modes with a time limit. For example, if a commuter uses two buses and Metro in one trip within a time window of two hours, then she/he would have to pay one ticket only, at the cost of one dollar approximately.

In this study, the Transantiago bus system is considered, due to the advantage of having real-time GPS markings, as well as covering more kilometers in network length and being the first alternative to travel for many Santiago residents. Moreover, access to GPS data allowed us to compute accessibility based on real operating conditions rather than planned schedules.

4. Data description

In this study, we base our analysis on real-time information about the public transportation system operation. This data comes from Transantiago authorities and consists of GPS information of all the

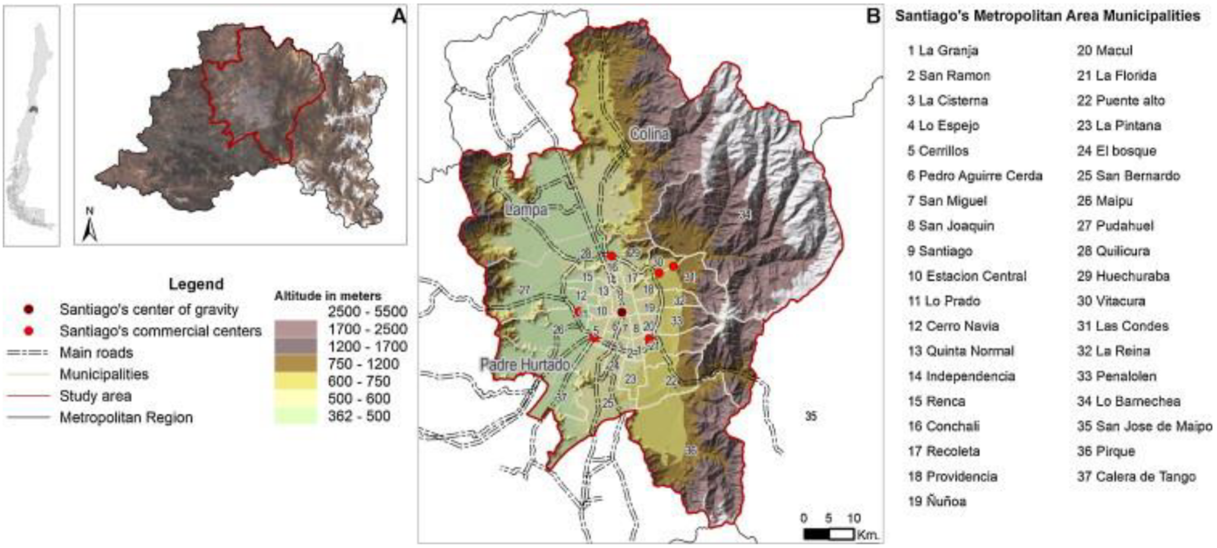

Fig. 1. Metropolitan area of Santiago (Puertas et al., 2014).

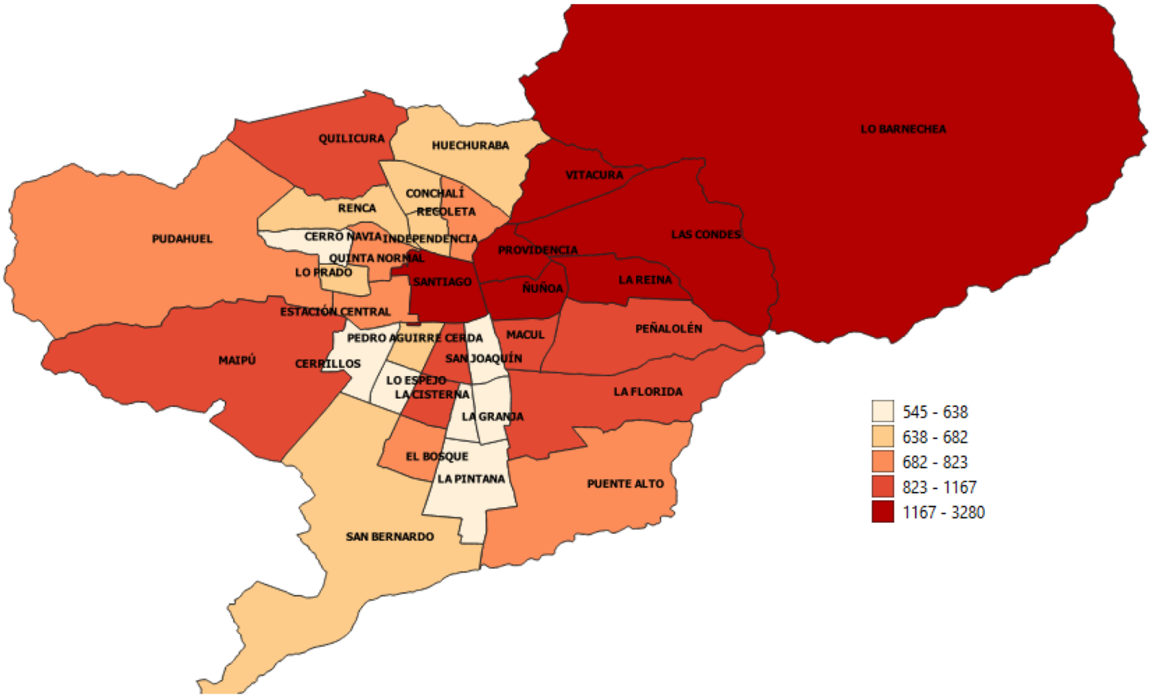

Fig. 2. Average individual income per municipality (USD). Source: National Statistics Institute.

buses of the system. Every 30 s, each bus identified by its plate and service number sends its latitude, longitude, and instant speed, giving a daily average of around 11 million observations. We complement this database with the service routes geocoded database to check the consistency of the service number reported. For this paper, we consider a single working week of data (from November 5th, 2018 through November 9th, 2018), in order to reduce the computational load. This leaves us with around 70 million GPS observations. GPS data from the Santiago buses system has been used in previous studies, for example, to estimate origin–destination matrices (Munizaga and Palma, 2012), to evaluate commercial bus speeds (Cortés et al., 2011), to detect public transport users' activities (Devillaine et al., 2012) and to model the bus bunching phenomenon (Arriagada et al., 2019), among others. Fig. 3 shows an example of the temporal evolution of GPS signals for different buses during the studied period.

In this paper, we consider a measure of accessibility computed as the number of opportunities (work, education, and healthcare) reached within a fixed amount of time. Concerning the educational institutions, there are four different types of institutions considered. For higher education, we compute accessibility measures for both universities and technical institutions, whereas, for schools, we consider primary and secondary institutions. We obtain the addresses of educational schools from the minister of education official website[1]. The data set consists of 4148 schools from which 3118 are currently operating. From these schools, 1218 of them provide high education while 2781 provide primary education. It is worth noting that some schools, located in the same address, provide both high and primary education. As we can see

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[1] www.mineduc.cl, accessed on November 12th, 2018

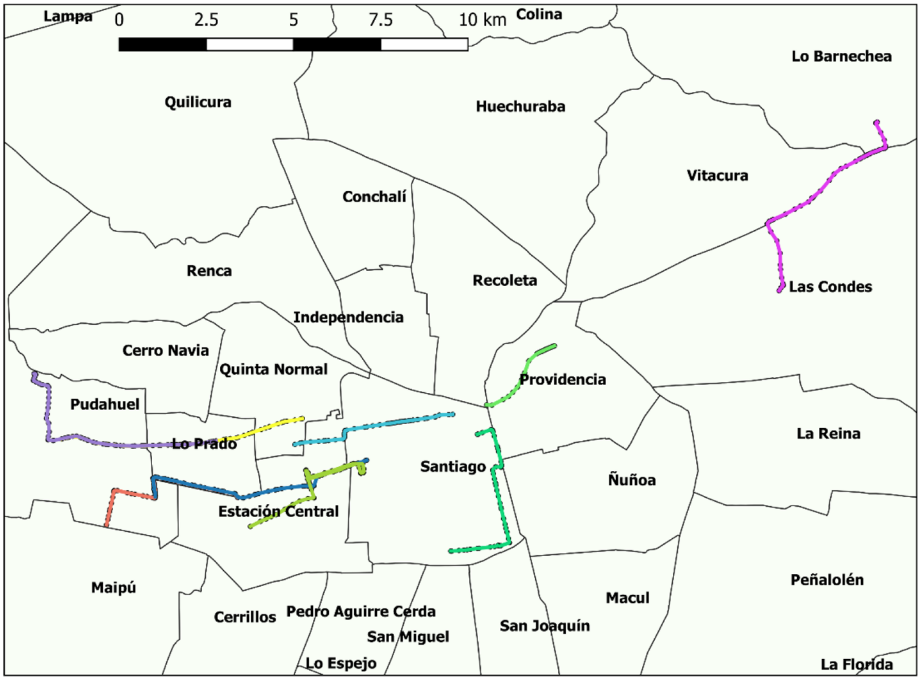

Fig. 3. Example of the spatial distribution of GPS signals.

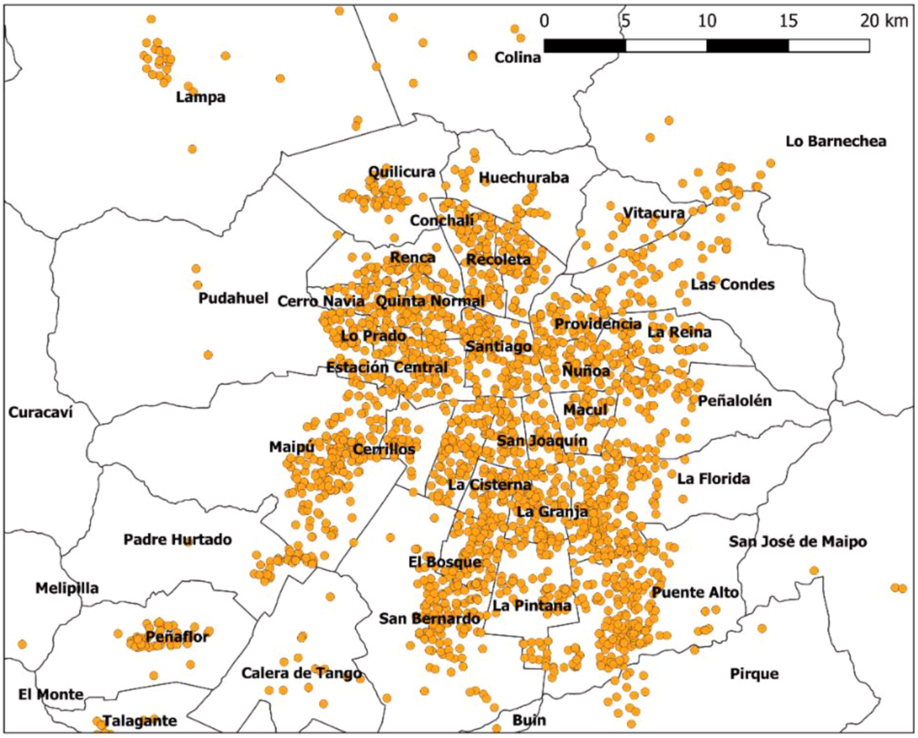

Fig. 4. Spatial distribution of schools providing primary education.

in Figs. 4 and 5, schools providing primary and high education, respectively, spread all over the region. Within each municipality, schools tend to be more concentrated in its center.

In this paper, we analyze the accessibility to two types of higher education institutions, namely, universities and technical schools. To obtain this information, we visit the official web pages of each institution, collecting the addresses of all the buildings. Our data set consists of 80 universities' buildings and 130 technical schools' buildings. We distinguish between buildings belonging to accredited institutions[2] and those belonging to unaccredited institutions. Figs. 6 and 7 show the spatial distribution universities and technical schools, respectively. Opposed to primary and high schools, higher education institutions are concentrated in the city center, while substantial portions of lands are not covered. Notably, in the west area of the region, very populated municipalities, such as Maipú, do not have any

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[2] www.cnachile.cl, accessed on August 10 th 2019.

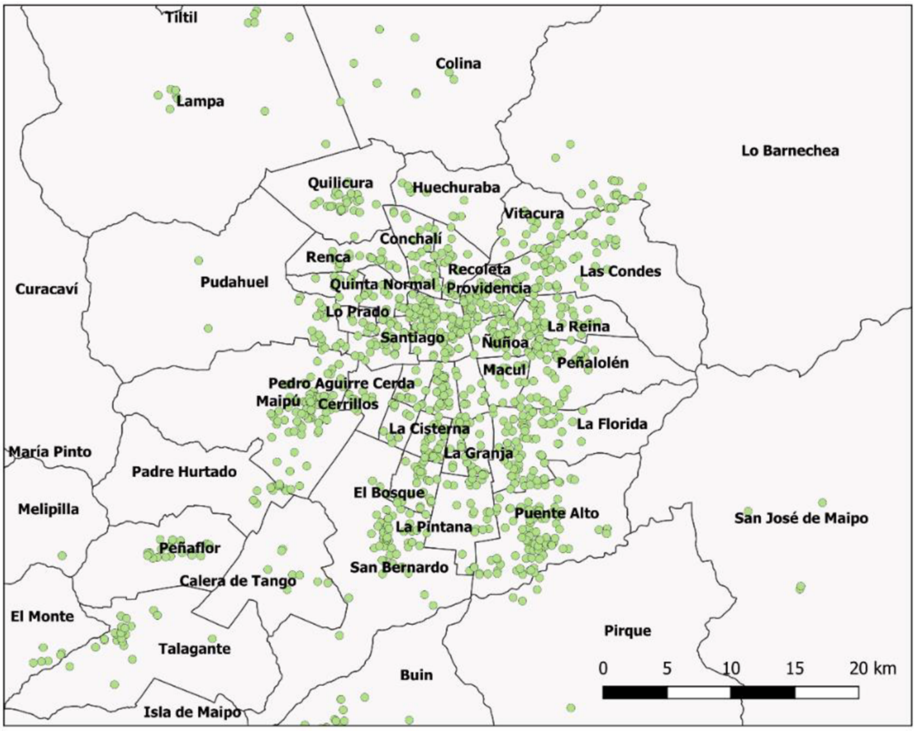

Fig. 5. Spatial distribution of schools providing secondary education.

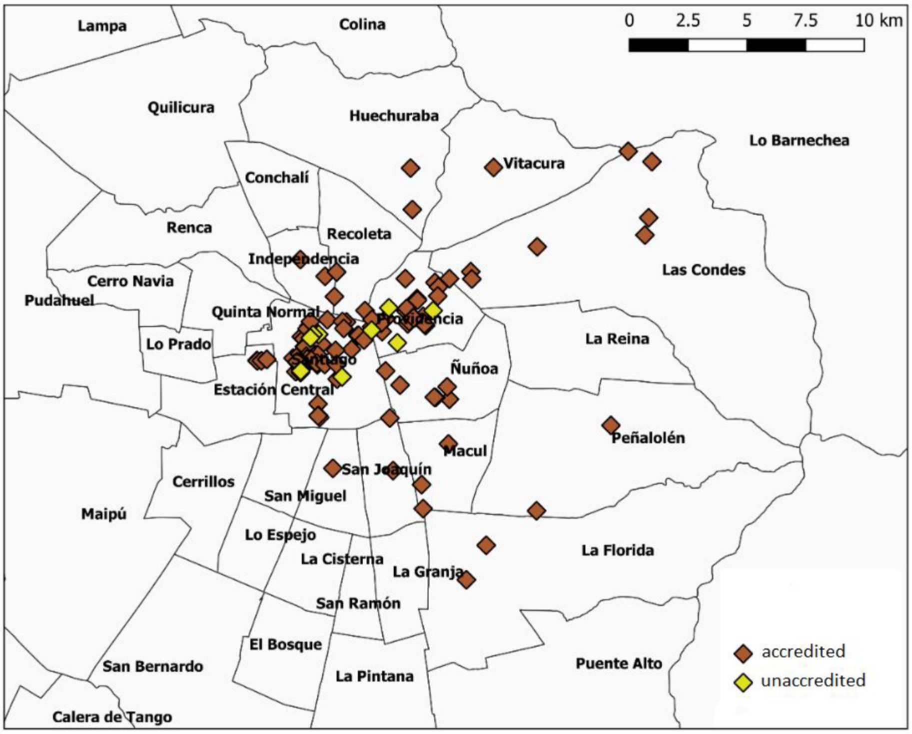

Fig. 6. Spatial distribution of universities.

university building.

We obtain the addresses of health institutions from the minister of health[3]. In this paper, we classify the health institutions in 5 categories, namely: primary (396), secondary (54), tertiary or high-complexity (36), private (97), and dental (106). The numbers in parenthesis correspond to the total number of institutions per category. The first three categories correspond to public services that vary from basic to more specialized services. Figs. 8 and 9 show the spatial distribution of public and private health institutions, respectively. We can see that private institutions are mainly located in Providencia, Las Condes, and Vitacura, the wealthier municipalities.

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[3] www.minsal.cl, accessed on August 10 th 2019.

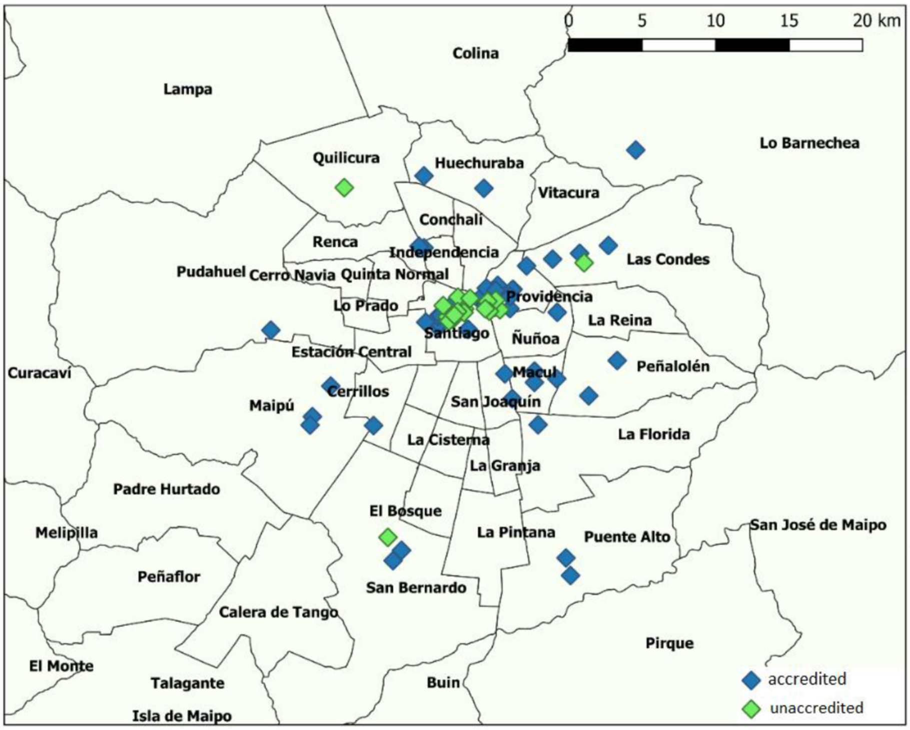

Fig. 7. Spatial distribution of technical schools.

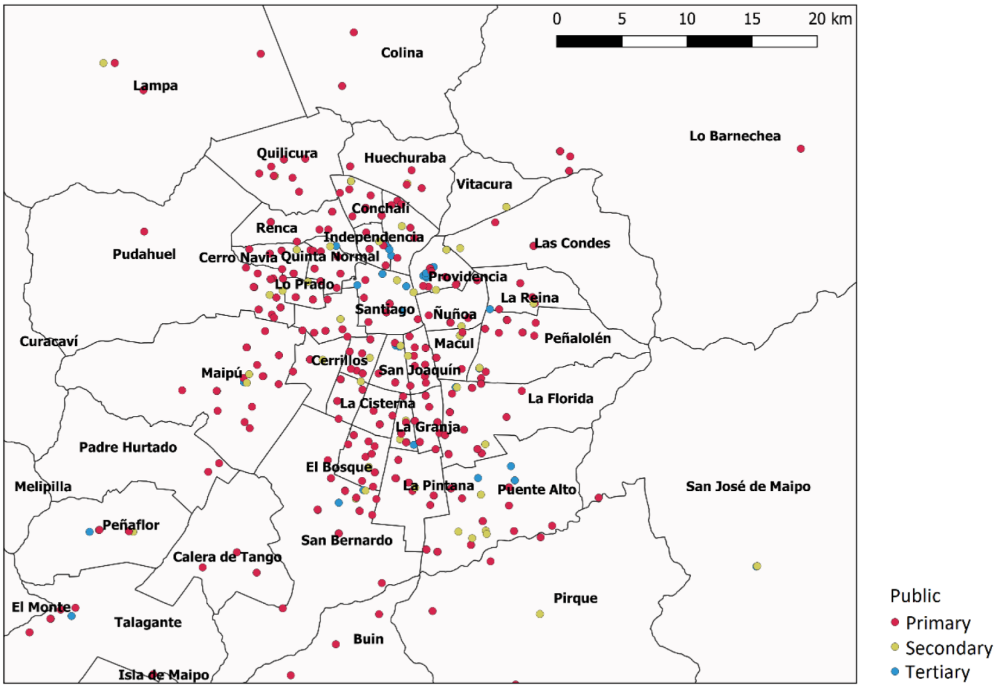

Fig. 8. Spatial distribution of public health institutions.

Finally, we obtain a proxy of job opportunities using the last origin–destination survey of Santiago[4]. Fig. 10 shows the spatial distribution of the number of travel destinations within this survey, having a “job purpose”.

5. Methodology

We divide Santiago using a geodesic discrete global grid system based in hexagons (Sahr et al., 2003). For this, we use the Uber H3 implementation[5]. The maximum distance between two points in the hexagon is set as 922 m implying that the whole area is walkable in less than 10 min. In our computational experiments, we found that the use

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[4] http://www.sectra.gob.cl/encuestas_movilidad/encuestas_movilidad.htm

[5] https://eng.uber.com/h3/

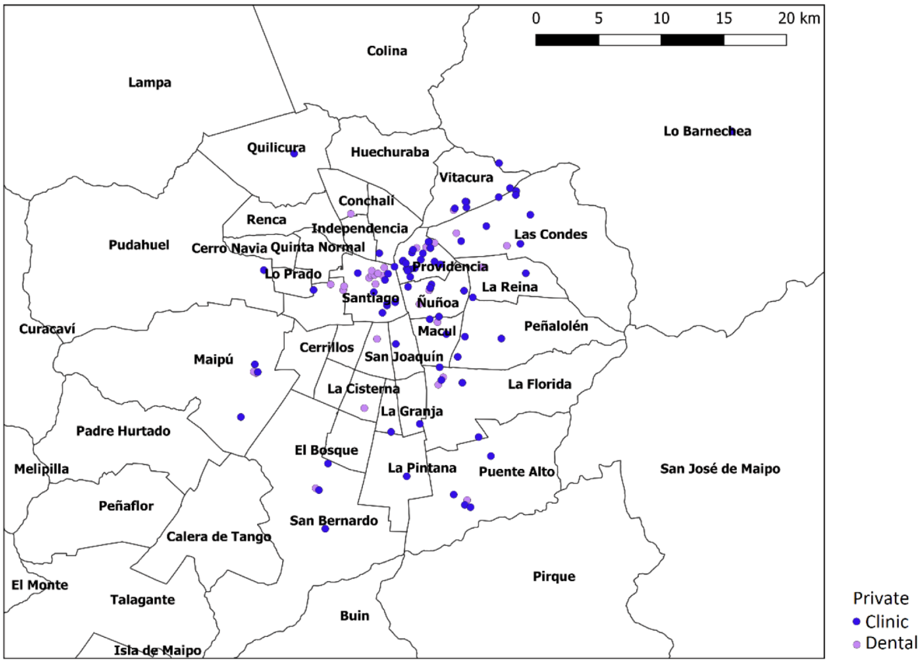

Fig. 9. Spatial distribution of private health institutions.

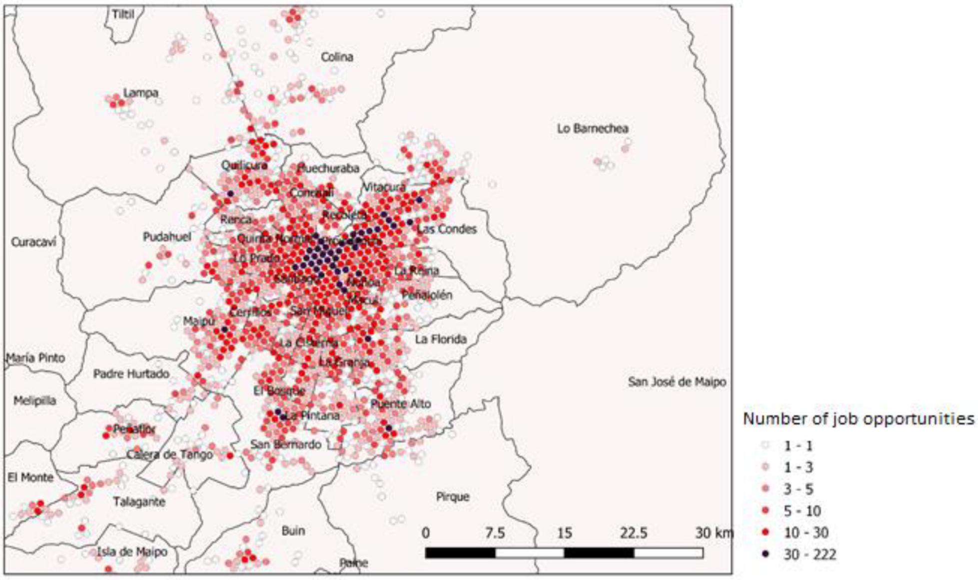

Fig. 10. Spatial distribution of job opportunities.

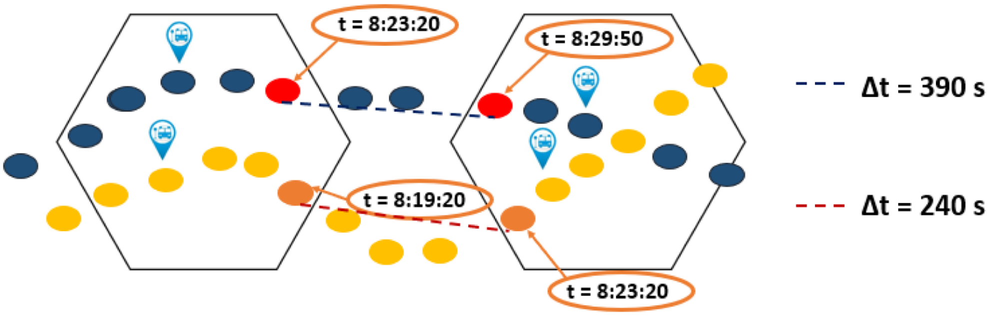

Fig. 11. Illustrative example of minimum travel time computation.

Table 1
Sets used for the computation of accessibility indicators.

D:	Days of the studied periods
I:	Hexagons
O:	Opportunity type (education, job or health)
M:	Municipalities
I_m:	Hexagons belonging to municipality $m \in M$

Table 2
Parameters used for the computation of accessibility indicators.

C_{ijd}:	Travel time by bus between hexagons $i \in I$ and $j \in I$ during the day $d \in D$
W_{ij}:	Travel time by walk between hexagons $i \in I$ and $j \in I$
Opp_{jo}:	Number of opportunities of type $o \in O$ in the hexagon $j \in I$
T:	Maximum travel time

of smaller hexagons reduces the chance of having a bus stop within considerably. On the other hand, the use of larger hexagons overlooks the need for using other transport modes to move within the hexagon. We assume that the time needed to go from a hexagon to another corresponds to the minimum travel time of any bus having at least one stop in both hexagons. For the sake of explanation, consider the example described in Fig. 11. In this example, two buses crossed the two studied hexagons. For the blue bus, the last GPS data in the origin hexagon (red point) was detected at 8:23:20, while the first GPS data for the destination hexagon was recorded at 8:29:50. Thus, for this bus, the travel time between both hexagons is 390 s. Similarly, the travel time between the two hexagons for the yellow bus is 240 s. To compute the final travel time, we repeat this process for all the buses crossing the two hexagons during the studied period, and we select the minimum travel time among them.

Tables 1 and 2 show the notation used for computing the accessibility measure.

For each day $d \in D$ and opportunity type $o \in O$, we compute the proportion of the opportunities reachable from the hexagon $i \in I$ in less

Table 3
Percentage of accessible opportunities from each municipality by bus or walking.

	Average accessibility (%)									
Municipality	Education				Labour	Health				
	School		Higher			Public			Private	
	Primary	High	Technical	University	Job	Primary	Secondary	Tertiary	Clinic	Dental
CERRILLOS	6.23	5.62	8.70	8.89	6.98	5.12	5.10	4.27	2.88	8.02
CERRO NAVIA	6.65	5.13	9.28	13.74	7.48	6.94	7.92	6.33	2.93	7.05
CONCHALI	6.37	6.02	13.36	13.81	12.00	6.52	7.25	12.45	3.10	11.76
EL BOSQUE	8.66	8.12	4.71	9.59	6.15	8.03	8.34	10.14	3.70	5.89
ESTACION CENTRAL	9.43	9.83	33.28	33.82	13.47	7.73	6.60	8.25	6.43	19.54
HUECHURABA	3.43	3.08	4.40	7.56	6.59	3.71	5.70	8.12	3.86	8.96
INDEPENDENCIA	7.83	8.82	33.30	34.02	17.58	6.62	8.72	23.76	7.50	20.98
LA CISTERNA	11.81	11.16	14.31	13.01	10.71	10.97	10.42	13.39	5.19	13.21
LA FLORIDA	7.95	8.15	8.50	5.15	6.16	6.05	8.35	7.61	7.81	8.53
LA GRANJA	11.10	10.55	9.02	6.24	9.11	9.85	11.56	11.19	7.95	11.17
LA PINTANA	6.35	6.22	3.59	2.31	4.02	6.01	8.67	9.50	4.55	4.25
LA REINA	5.42	8.18	15.94	11.32	10.54	4.38	6.89	9.32	13.21	13.30
LAS CONDES	3.38	5.87	15.81	12.45	11.84	2.11	6.09	11.01	15.38	11.74
LO BARNECHEA	0.81	1.53	4.01	1.99	2.68	1.11	3.16	6.96	7.53	4.55
LO ESPEJO	7.86	7.00	11.20	14.89	8.25	7.55	6.19	7.81	1.89	7.81
LO PRADO	9.07	8.03	27.58	29.78	12.85	9.16	10.78	6.39	4.56	15.05
MACUL	8.12	9.67	19.44	16.70	11.01	7.82	10.11	12.97	16.97	14.93
MAIPU	5.46	5.41	7.74	13.58	4.94	3.79	3.86	2.91	2.79	7.09
NUNOA	8.80	12.80	39.07	37.15	18.30	6.84	11.89	20.81	24.99	22.41
PEDRO AGUIRRE CERDA	8.46	8.23	26.25	33.10	11.72	8.54	8.97	11.48	4.89	12.14
PENALOLEN	3.81	5.13	7.51	5.55	4.30	3.78	6.59	6.33	6.97	8.21
PROVIDENCIA	7.48	11.20	38.81	40.33	22.21	5.37	9.10	23.82	30.39	24.58
PUDAHUEL	2.48	2.09	7.80	17.39	2.71	3.16	4.63	4.42	2.65	8.70
PUENTE ALTO	6.01	6.24	3.16	1.86	3.41	4.25	10.55	7.90	4.74	4.24
QUILICURA	2.61	2.44	4.55	4.32	4.48	2.81	3.62	5.84	2.75	7.06
QUINTA NORMAL	8.53	7.99	28.25	31.28	14.09	7.92	9.00	12.19	5.72	15.29
RECOLETA	6.59	6.75	16.73	19.49	14.27	6.13	10.81	20.00	10.90	12.15
RENCA	4.61	4.02	9.50	10.34	6.61	4.50	4.83	10.83	4.05	9.78
SAN BERNARDO	2.94	2.85	4.74	15.60	2.48	2.63	4.60	4.39	2.23	4.78
SAN JOAQUIN	9.77	10.69	24.08	21.53	15.41	8.45	12.64	16.85	11.52	18.79
SAN MIGUEL	11.71	11.76	21.69	22.55	15.56	11.65	15.31	17.53	8.51	18.12
SAN RAMON	12.59	12.23	12.25	11.03	10.55	11.02	14.31	16.62	8.30	11.49
SANTIAGO	14.98	16.83	50.24	59.75	27.19	13.48	16.15	27.94	19.78	33.13
VITACURA	2.18	3.69	9.50	5.21	8.88	1.36	4.31	8.07	12.50	8.69
Average	**7.04**	**7.45**	**16.13**	**17.22**	**10.13**	**6.33**	**8.32**	**11.39**	**8.21**	**12.16**
Standard Deviation	**3.24**	**3.44**	**11.94**	**13.05**	**5.69**	**2.99**	**3.32**	**6.12**	**6.58**	**6.42**

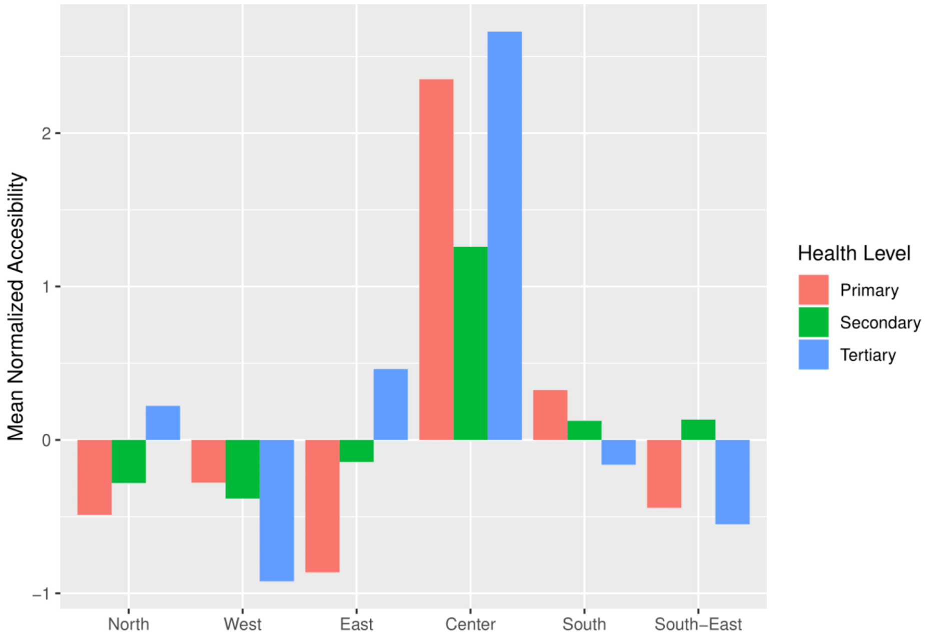

Fig. 12. Mean normalized accessibility to public health, grouped by sectors.

than T minutes compared to all opportunities of type $o \in O$ using Eq. (5), where $1_{\min\{C_{ijd},W_{ij}\}\le T}$ denotes the indicator function, taking value 1 if $C_{ijd} \le T$ or $W_{ij} \le T$, and 0 otherwise. Note that we include in the computation of accessibility measures the opportunities reachable in less than $T = 30$ minutes walking, which enables us to analyze the marginal contribution of public transport when accessing opportunities. We use a proxy of walking time to opportunities, considering the Euclidean distance between them and the center of every hexagon. Then, we consider an average walking speed of 5 km/h, which is a common assumption in the relevant literature.

$$A_{iod} = \frac{\sum_{j\in I} Opp_{jo}\cdot 1_{\min\{C_{ijd},W_{ij}\}\le T}}{\sum_{j\in I} Opp_{jo}} \tag{5}$$

Finally, we determine accessibility per municipality, averaging over the hexagons that belong to each municipality using Eq. (6).

$$\bar{A}_{mo} = \frac{1}{|D|\cdot|I_m|}\sum_{d\in D}\sum_{i\in I_m} A_{iod} \tag{6}$$

6. Computational results

Our case study considers the week ranging from November 5th, 2018, through November 9th, 2018 ($|D| = 5$). We use $|I| = 1,390$ hexagons, and we consider a threshold $T = 30$ minutes. We select this week because it does not have exceptional circumstances such as holidays, unexpected weather, or protests so that it could be considered as a representative week for Santiago's mobility. We use Eq. (6) for each municipality covered by the public buses system ($|M| = 34$, excluding San José de Maipo, Pirque and Calera de Tango), and ten opportunity types ($|O| = 10$). These include four education opportunity types (primary, secondary, universities, or technical schools), five healthcare opportunity types (primary, secondary, tertiary, private, or dental), and job opportunities.

Table 3 shows the results. The three most accessible opportunity types are universities, technical schools, and dental centers. These opportunities are located in areas with good access to public transport, so the contribution of buses is significant. The maximum standard deviation corresponds to universities and technical schools. This last is because higher education institutions are not present in all the sectors of the city, e.g., the west zone has none while the east area has several. As expected -by historical reasons-, Santiago is the municipality with the highest accessibility to all types of opportunities but private clinics, where Providencia leads, followed by Nuñoa. An explanation for this result is that clinics are spread unevenly in the city. As Fig. 9 depicts, most are located in the north-east sector.

When we contrast the results of Table 3 with municipalities' income level, we can see that as the level of public health institutions complexity increases, so does the relative accessibility in the sectors with the highest income in the city. The opposite pattern is present in areas with low income. This finding is depicted in Fig. 12, showing the mean values, weighted by the population of each municipality, of normalized accessibility levels to public health. We normalize values to compare relative accessibilities to institutions with different densities over the city. The municipalities are grouped using the same zonification used in the last origin–destination survey in Santiago. In particular, the lowest income residents of Santiago (located in the South and West) have above-average access to primary health institutions, but below-average access to tertiary health. This pattern reverses for the residents of the East sector, the ones with the highest average income.

To separate the impact of land use and public transport over the accessibility to opportunities, Table 4 shows the marginal contribution of public transport, i.e., the accessibility percentage gained when adding public transport to a base situation where only walking is possible. The results show that universities have the maximum gain (12.7%) because they locate in particular places in the city (Fig. 6), so several surrounding hexagons can reach them by bus but not by walking. Conversely, the gained percentage of clinics is low (5.04%), so for the majority of the population, clinics are not accessible, neither by walk nor by bus. This can be explained because the location of clinics follows market trends, so wealthier municipalities, which are usually located in the north-east part of the city, have a higher density of private health institutions (Fig. 9). Public primary health centers have the lowest gain (3.61%) by the effect of the buses because this kind of infrastructure is much more homogeneously distributed throughout the city since their locations are part of public policies aimed to ensure universal accessibility.

To get a sense of Santiago inequality, Fig. 13 shows the correlation between accessibility to opportunities and income. Some of the most desirable opportunities (jobs, clinics, dental institutions) are accessible only for the residents of the high-income municipalities. As mentioned

Table 4
Gained accessibility due to buses compared to walking.

	Average accessibility (%)									
Municipality	**Education**				**Labour**	**Health**				
	School		**Higher**			**Public**			**Private**	
	Primary	**High**	**Technical**	**University**	**Job**	**Primary**	**Secondary**	**Tertiary**	**Clinic**	**Dental**
CERRILLOS	3.83	3.85	7.33	8.89	4.74	2.51	2.44	4.27	1.51	4.61
CERRO NAVIA	3.39	3.54	9.28	13.74	6.02	2.71	3.40	3.55	1.83	7.05
CONCHALI	3.67	4.37	11.21	13.04	9.77	3.28	5.08	8.98	3.10	9.49
EL BOSQUE	4.83	5.24	2.35	9.59	4.23	4.06	4.25	6.57	2.61	3.62
ESTACION CENTRAL	6.18	6.78	19.70	18.55	9.91	4.53	3.60	5.48	5.23	13.64
HUECHURABA	2.11	2.22	3.13	6.19	4.98	1.99	3.40	8.12	2.83	6.69
INDEPENDENCIA	4.30	4.84	26.06	22.96	11.24	4.00	5.30	9.87	5.44	15.56
LA CISTERNA	7.46	7.22	14.31	12.24	8.22	7.26	7.28	10.62	4.16	10.94
LA FLORIDA	4.58	4.87	7.00	3.46	4.48	3.51	5.45	3.63	5.71	4.38
LA GRANJA	7.18	7.45	7.45	5.24	6.77	4.70	6.12	8.41	5.96	7.76
LA PINTANA	4.14	4.32	3.59	2.31	3.05	3.12	5.53	6.46	3.03	4.25
LA REINA	3.47	5.38	14.30	10.36	8.46	2.62	4.24	6.55	11.26	9.89
LAS CONDES	2.17	3.48	11.53	9.49	7.58	1.47	3.35	7.53	10.09	5.80
LO BARNECHEA	0.47	0.91	2.84	0.86	2.12	0.38	1.30	6.96	4.71	4.55
LO ESPEJO	5.19	5.23	10.02	14.89	6.30	4.59	3.64	7.81	1.89	5.54
LO PRADO	4.95	5.40	26.40	26.90	10.18	4.43	5.41	6.39	3.32	11.64
MACUL	5.36	6.80	12.96	12.85	7.71	4.15	4.93	8.27	11.35	10.73
MAIPU	3.10	3.10	5.68	13.58	3.42	2.20	0.81	0.13	1.26	3.22
NUNOA	5.37	7.48	32.14	28.75	12.47	4.08	7.87	14.77	13.89	14.55
PEDRO AGUIRRE CERDA	4.77	5.23	22.72	30.54	8.54	4.89	3.99	2.59	3.17	9.87
PENALOLEN	2.20	3.08	5.38	4.56	3.22	1.98	3.18	3.11	4.49	5.68
PROVIDENCIA	4.74	6.36	17.69	16.38	10.38	3.33	3.95	7.15	9.01	13.12
PUDAHUEL	1.51	1.43	6.62	17.39	2.02	1.08	0.19	4.42	1.62	8.70
PUENTE ALTO	3.55	3.56	1.10	1.86	2.33	2.84	5.89	2.90	2.51	1.96
QUILICURA	1.48	1.19	3.37	4.32	2.87	1.41	1.50	5.84	0.68	7.06
QUINTA NORMAL	4.46	4.80	23.65	21.52	10.70	4.22	5.11	7.87	4.48	9.77
RECOLETA	3.78	3.75	4.18	6.21	7.42	3.64	6.68	5.42	2.82	3.48
RENCA	2.43	2.56	7.25	9.57	5.11	2.08	2.20	7.55	4.05	7.51
SAN BERNARDO	1.64	1.66	2.23	15.60	1.43	1.32	1.07	0.35	0.71	2.51
SAN JOAQUIN	6.54	7.44	20.24	17.68	11.37	4.47	9.06	9.59	8.49	15.47
SAN MIGUEL	7.60	7.71	19.92	20.04	11.86	7.82	9.88	8.37	6.45	15.85
SAN RAMON	8.07	8.16	12.25	10.26	8.25	5.96	9.93	13.84	6.59	9.21
SANTIAGO	11.24	11.15	15.65	18.41	14.90	11.03	12.50	15.00	11.03	16.18
VITACURA	1.43	2.11	6.87	3.55	5.32	0.93	1.87	5.29	6.07	4.28
Average	**4.33**	**4.78**	**11.66**	**12.70**	**6.98**	**3.61**	**4.72**	**6.87**	**5.04**	**8.37**
Standard Deviation	**2.25**	**2.30**	**8.08**	**7.72**	**3.45**	**2.11**	**2.77**	**3.44**	**3.38**	**4.18**

Fig. 13. Correlation between income and accessibility to opportunities by public transport.

before, this is strongly related to the geographical distribution of opportunities. An important implication of this is that public transport does not alleviate this inequality.

Fig. 14 shows the correlation between income and gained accessibility due to public buses. Even though from a redistributional point of view, the desirable outcome would be, for example, a negative correlation between income and gained accessibility to jobs -in order to offset the geographical distribution of opportunities- the opposite happens.

Fig. 15 shows a disaggregated perspective of job opportunities accessibility. As discussed in Section 1, the economic center has progressively moved to the north-east part of the city. In particular,

Fig. 14. Correlation between income and gained accessibility due to buses.

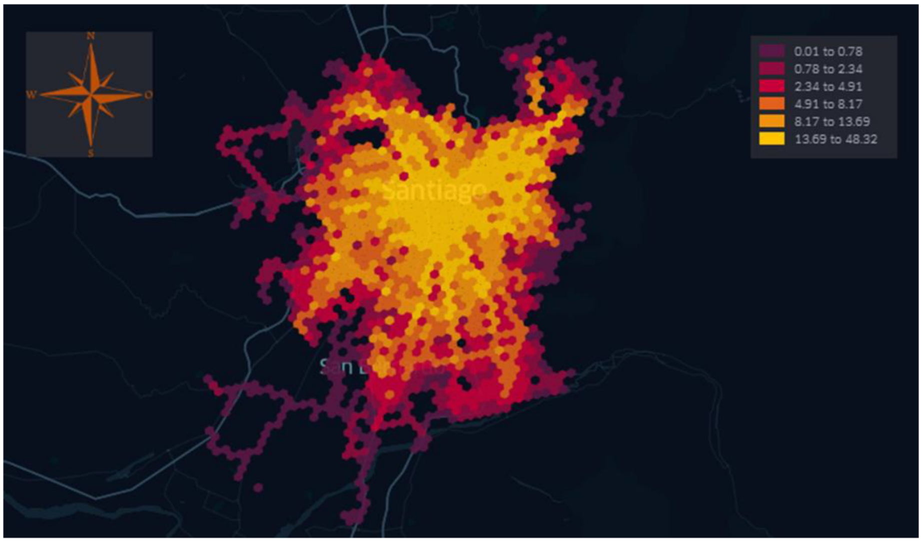

Fig. 15. Public transport accessibility to job opportunities disaggregated by hexagons.

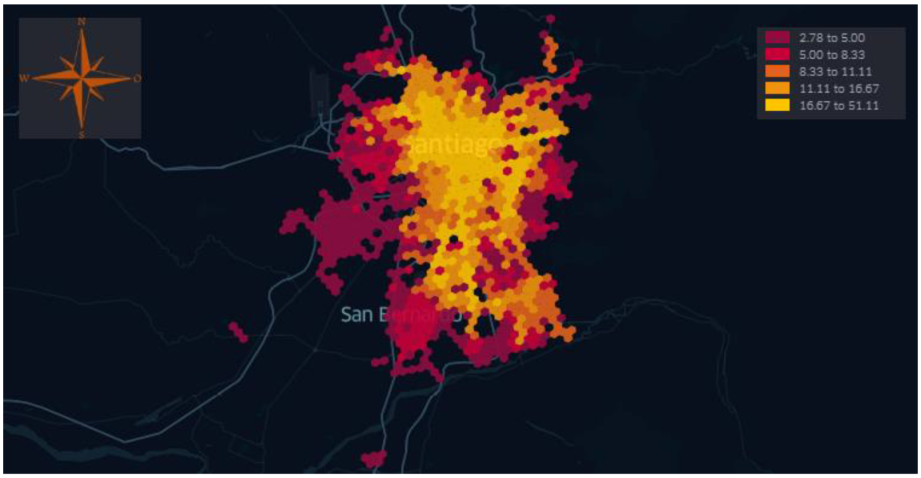

Fig. 16. Public transport accessibility to tertiary public health disaggregated by hexagons.

companies have relocated offices and headquarters to municipalities such as Providencia and Las Condes. Consequently, very populated and low-income municipalities, which are mainly located in the south part of the city, shows poor access to jobs, being left out of the economic progress. This is also shown in Fig. 13, where a positive correlation between job access and municipality income is present.

Fig. 16 shows a disaggregated perspective of complex/tertiary hospital accessibility. In this case, the west part of the city is poorly served with tertiary health. For example, Maipú, which accounts for 7.30% of the Santiago population, has the lowest accessibility (2.91%). This number does not decrease much when public transport is excluded (0.13%). This shows that public transport offer is not able to cope with the scarcity of this kind of infrastructure near the west sector.

Finally, in line with our previous analysis, we found that higher accessibility correlates with other quality of life variables other than income. For this, we consider the Quality of Urban Life Index[6] (Spanish

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[6] https://www.cchc.cl/comunicaciones/noticias/indice-de-calidad-de-vida-urbana-icvu-2018

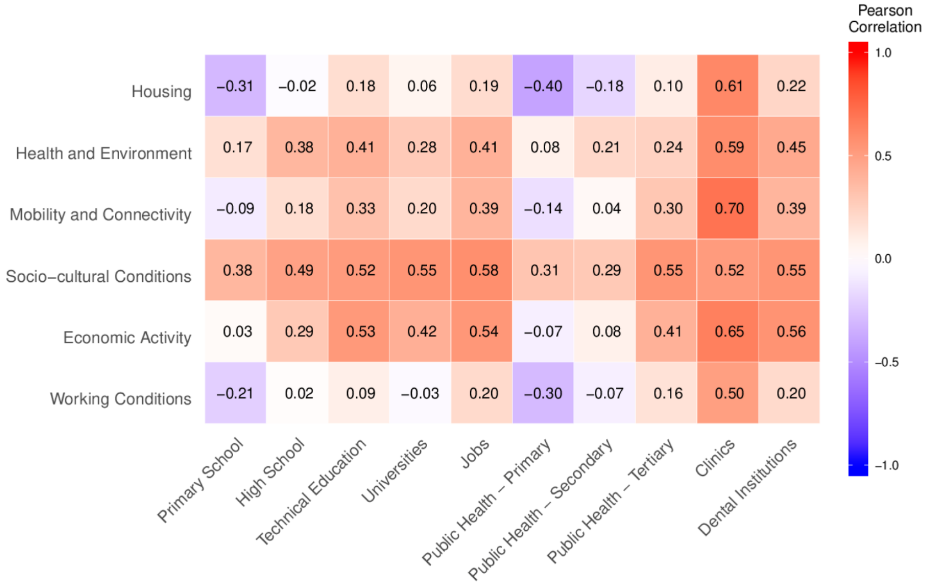

Fig. 17. Correlation between accessibility by public transport (x-axis) and ICVU 2018 indicators (y-axis).

acronym, ICVU) that measures and compares in relative terms the quality of urban life in municipalities and cities in Chile. This index is based on a set of variables related to six dimensions that reflect the provision of public goods and services. When comparing the values obtained by this index for each dimension and municipality with the accessibility values presented in Table 3, we can see there is a strong correlation between some of them (Fig. 17). In particular, accessibility by bus to clinics shows a strong positive correlation with all of the dimensions measured by the ICVU index. This has a straightforward interpretation: municipalities with high accessibility to clinics are those with the highest average income (Vitacura, Las Condes, etc.) since clinics' location is a result of market competition, where no public policy takes place. Thus, it is of no surprise that accessibility correlates with a higher standard of living in different aspects, as measured by the ICVU index. For basic public goods, such as primary school or health centers, the correlation is mainly negative. For example, public health and housing have an inverse relationship, i.e., accessibility is higher in municipalities with lower housing quality. An explanation is that poorer municipalities have a relatively higher density of this kind of infrastructure. Overall, the results seem to be linked mainly to land use rather than the transport system.

7. Discussion and conclusions

In this paper, we study the effect of the public bus system over the accessibility to education, health, and job opportunities in Santiago, Chile. To do so, we use full real-world GPS data to determine travel times between 1390 zones all around the city, and we compute an integral accessibility measure for each municipality. Our main finding is that public transport is not able to alleviate inequality throughout the city, given by the geographical distribution of opportunities. Indeed, some municipalities with the lowest income are excluded from job opportunities (south area) and complex health institutions (west area) when traveling by bus. This, in turn, deepens social inequality, isolating low-income people who usually present more constraints in their location and transportation mode choice (Liu and Kwan, 2020).

Three directions for public policy follow to improve this situation. In the short term, there is a need for policies aiming to mitigate inequalities by improving the quality of service in public transport. Examples include the expansion of the bus system (Power, 2012), more dedicated bus lanes (Basso and Silva, 2014), congestion charge (Batty et al., 2015), and better traffic control systems (Cortés et al., 2010). In the midterm, more infrastructure and transit systems redesigns could enhance accessibility. On the one hand, literature shows the benefits of providing bus rapid transit (BRT) to diminish travel times (Wirasinghe et al., 2013), making farther opportunities reachable while improving users' experience (Wu et al., 2020). Major transit systems redesigns (Lee and Miller, 2018), on the other hand, could incorporate information about the lack of some specific opportunities in deprived zones. In the case of Santiago, we believe our research results could support policymakers in rerouting the Transantiago buses network. Finally, in the long term, better city planning is required to facilitate the spreading of opportunities all over the city. Devising targeted subsidies could help in this matter, boosting sub-centers' consolidation in municipalities with low accessibility, and consequently, bringing opportunities closer to disadvantaged areas. Social housing policies have been successful in providing shelter to needed people, but they usually have not taken accessibility into account. The implementation of this type of policy in the peripherical municipalities decrease accessibility and increase social segregation (Martínez et al., 2018).

Further research on this topic is definitely needed. Even though we focus on buses because of the availability of GPS information, it is necessary to include Metro in order to broaden the scope of the analysis. Besides, it would be useful to vary the travel time threshold to carry on sensitivity analyses, studying the robustness of the results. Instead of the minimum criteria we use in this paper, different rules to determine travel times could be applied, such as maximums or averages. Moreover, an accessibility cost-benefit analysis could be pursued to focus public spending on the most deprived areas (Lucas et al., 2016), modifying operational planning and routes services to achieve maximum value for money.

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