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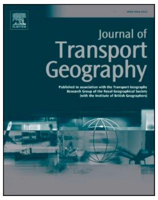

Impact of Quito's first metro line on the accessibility to urban opportunities

Adriana Quezada Larriva *, Daniel Orellana, María Laura Guerrero Balarezo, Javier Andrés García, Galo Cárdenas Villenas, Pablo Osorio Guerrero

LlactaLAB Ciudades Sustentables, Universidad de Cuenca, Av. 12 de Abril, Cuenca, Ecuador

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ABSTRACT

One of the main challenges for cities is to provide equitable access to urban opportunities such as commerce, jobs, recreation, and other facilities and services. Several cities are planning and building mass public transport systems to overcome the accessibility gap derived from urban sprawl, spatial exclusion, and extreme land-use specialization. Nevertheless, there is no information on how these transportation projects will impact overall and relative accessibility for different population groups, especially those with current low accessibility. This study proposes a rigorous and replicable methodology to measure the impact of public transport projects on the overall accessibility and accessibility gap to urban opportunities for different socioeconomic groups. The methodology comprises three main phases: i) the characterization of accessibility to urban opportunities through public transport; ii) the measurement of the accessibility gap between socioeconomic groups, and iii) the impact of the metro's implementation on accessibility and the gap. All the procedures were implemented using open-source software and publicly available data, guaranteeing transparency and replicability. We applied this methodology to analyze the impact of implementing the First Metro Line (PLMQ) in Quito, Ecuador. The results show that the PLMQ will increase overall accessibility to urban opportunities, and this impact depends on travel time and current accessibility levels. The impact of the PLMQ on the accessibility gap will be more modest, and the benefits will be more important at long travel times. We argue that incorporating this kind of analysis on early planning phases of public transport projects will allow better planning and design decisions and inform public debate about significant investments in sustainable mobility.

1. Introduction

In recent decades, the study of transport and its relationship with social exclusion has gained considerable interest in the framework of human rights and mobility planning (Guida and Caglioni, 2020; Kamruzzaman et al., 2016). Social exclusion is understood as the process in which an individual or group of individuals is deprived of access to essential opportunities and participating in economic, civic, and cultural life in a given territory (Murray and Davis, 2002; Tan et al., 2018).

This process is exacerbated and mainly impacts the poorest population groups, living in peripheral and marginal areas, where the public transport system tends to be difficult to access or non-existent (Yáñez-Pagans et al., 2018). In light of this situation, several studies have shown that one way to mitigate and prevent social exclusion and reduce inequalities between social groups consists of expanding the population's accessibility to opportunities through implementing an adequate public transport system (Tan et al., 2018). Access to a public transport system is important for overcoming social disparities (Vecchio et al., 2020; Yáñez-Pagans et al., 2018). It guarantees the right to mobility, which enables other rights (Heinrichs and Bernet, 2014; Saif et al., 2019). This condition has gained more interest in contexts where a city's growth, spatial dispersion, and increasing population demand implementing public transport systems with greater capacity and efficiency to strengthen these rights (Vecchio et al., 2020). Thus, several cities have adopted mass public transport systems, such as the bus rapid transit (BRT), the tram, the subway, among others. In some cases, implementing these systems has contributed to reducing social exclusion by serving mainly populations with limited economic resources and those marginal or peripheral to urban centers. In other cases, their implementation has not had favorable results (Manaugh and El-Geneidy, 2012; Oviedo et al., 2019); accessibility to job and health opportunities have worsened for some population segments since these systems have failed to integrate

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* Corresponding author at: LlactaLAB Ciudades Sustentables, Universidad de Cuenca, Av. 12 de Abril y Av. Loja, Cuenca, Ecuador.
E-mail addresses: adriana.quezada@ucuenca.edu.ec (A. Quezada Larriva), daniel.orellana@ucuenca.edu.ec (D. Orellana), maria-laura.guerrero-balarezo@polymtl.ca (M.L. Guerrero Balarezo), javier@ubica.ec (J.A. García), gc@cercana.ec (G. Cárdenas Villenas).

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into the urban and mobility structure (Guzman et al., 2018; Barboza et al., 2021; Costa et al., 2021).

For this reason, governments and decision-makers must have timely information, easy to interpret and understand, that guides urban mobility planning and guarantees sound investments, especially in places with limited economic resources (Papa et al., 2016). In this regard, the measurement of accessibility to opportunities based on the calculation of cumulative opportunities is considered the most popular and effective tool to guide mobility planning, due to its theoretical soundness (it captures the interaction between land use and transportation systems), its operational ease, its adequate level of aggregation, and its high communicability and transferability (Papa et al., 2016; Bantis and Haworth, 2020). Most accessibility studies analyzed the accessibility of the general population at the aggregated level, and a few focused on specific social groups (R. Liu et al., 2018; Vecchio et al., 2020). Nevertheless, most studies relying on CUM or gravity-based models analyze accessibility based on a predetermined cut-off time (e.g. based on average travel time) for each specific location (Barboza et al., 2021), failing to capture the inequalities across different travel times.

Also, those measures are usually reported aggregated at the area level (neighborhood, district, etc.), and therefore assume a socio-economical homogeneous population inside each area. Moreover, to our knowledge no prior studies have focused on how mass transportation projects modify the gap between the accessibility of different socio-economic groups in Latin America.

The aim of this study is twofold. On the one hand, it presents a replicable methodology to assess the potential impact of public transportation projects on the spatial accessibility to urban opportunities, focusing on the accessibility gap between socioeconomic groups and using open source and public available data. On the other hand, analyses the impact of the First Metro Line in Quito, Ecuador (PLMQ, from Spanish “Primera Línea del Metro de Quito”) using the proposed methodology to answer the following questions: a) What is the current level of accessibility of the population of Metropolitan District of Quito (MDQ) to urban opportunities using public transport? b) Is there an accessibility gap in public transport associated with the population’s living conditions? c) To what extent will the implementation of the PLMQ impact the population’s accessibility? And d) To what extent will the PLMQ’s implementation modify the accessibility gap?.

For this purpose, a spatial-temporal accessibility model was used that includes components related to land use, the public transport system, and the population’s socioeconomic characteristics. This model realistically captures travel times, optimal route identification, the transportation system facilities, and the built environment’s characteristics that determine mobility. This methodology is based on the use of open source software and data provided by local governments, which guarantees its replicability.

2. Related work

There exists a considerable body of literature studying spatial inequality based on the measurement of accessibility to opportunities depending on the public transport system. Over time, an extensive literature has developed on the North countries, especially in the United States and European countries (Proffitt et al., 2019). This approach has gained interest in Latin America, as it is one region where the process of social exclusion has been exacerbated due extreme poverty and inequality as well as the dependance on inefficient public transport and urban sprawl (Vecchio et al., 2020).

Accessibility to opportunities refers to the capability and/or possibility an individual or a specific population has to adequately and timely access different urban facilities through different means of transport (Vecchio et al., 2020). The study of accessibility to opportunities is based on the relationship between three main components: i) land use, ii) the transportation system, and iii) individual and population characteristics (Bantis and Haworth, 2020; Guida and Caglioni, 2020), and it is inevitably linked to social groups’ spatial exclusion. The latter is expressed not only in the residence location but also in the accessibility levels to work, services, and other opportunities that tend to be physically concentrated around a city’s central and business districts (Oviedo et al., 2019).

According to Vecchio et al. (2020), in Latin America accessibility studies have been addressed along: Argentina, Bolivia, Brazil, Colombia, Chile, Peru and Uruguay; being the most studied cities Sao Paulo, Santiago de Chile and Bogotá. The main purpose that conducted these studies are: i) analyze the existing inequity between socioeconomic groups to access a specific opportunity (Vecchio et al., 2020); and ii) evaluate the impact on accessibility when implementing or modifying the public transport system. (Guzman et al., 2018; Pereira, 2019).

Accessibility to opportunities has been analyzed mainly from a geographical and temporal dimension, based on the calculation of cumulative opportunities. However, the approach and parameters used are diverse. The characterization of trips differs from one study to another, when outlining access to public transportation and travel times. Mobility by foot is the most common mode employed for the analysis of accessibility to public transport (Saif et al., 2018). Proximity buffers (transportation coverage from stations) (Oviedo et al., 2019; Boisjoly et al., 2020) or surveys (Hernandez, 2018) were used to capture time and distance of walks to stations. However, these methodologies fail to realistically represent pedestrian mobility by not considering impedance factors such as the spatial configuration of road network, slopes, pavements, among others (Tiznado-Aitken et al., 2018).

Regarding the customization of travel times, most studies were limited to locate and analyze certain data (public transport routes, population, land use and their areas of influence) by the use of geographic information systems (GIS) (Hernandez, 2018; Pucci et al., 2019; Lessa et al., 2019). In most of the cases, travel routes and travel times were obtained with mobility surveys overlooking platforms such as Google Maps Distance Matrix API, and Google Transit Feed Specification (GTFS). The former, includes multimodal travel time information and alternative trajectory; and the latter, gives detailed information on the operation of public transport. The use of the GTFS has been limited to a few studies in Latin America due to the lack of data (Slovic et al., 2019; Pereira, 2019; Boisjoly et al., 2020). Travel time requires more reliable representation of the public transport operation and its components, such as times of departure, arrival, transfer; traffic, number of stations, schedule, etc. (Boisjoly et al., 2020).

Most studies in the region have focused on examining inequalities in job accessibility (Vecchio et al., 2020). They have contributed to a better understanding of the factors that affect the low-income population accessing job opportunities in urban areas, compared to other socio-economic groups. Both baseline and scenario studies describe accessibility to job opportunities dependent on diverse variables such as: travel costs (in time and distance) (Hernandez, 2018), affordability (Bocarejo et al., 2014), attractiveness of location (Bocarejo et al., 2014), balancing time indicator (Barboza et al., 2021), and quality of public transportation (Pucci et al., 2019).

The results of these studies evidence that the low-income population has less accessibility to job opportunities as a consequence of the great distances between their homes and formal job supply; which tends to be concentrated in centralities. It has also shown that the improvements made in the public transport system do not always enhance the accessibility of the poorest in society. Studies conducted in Medellín, Lima, Sao Paulo, and Bogota exemplify this outcome (Bocarejo et al., 2014; Oviedo et al., 2019; Boisjoly et al., 2020). Finally, all studies have demonstrated that there is a gap in accessibility to urban opportunities between different socioeconomic groups. Even though the gap is frequently explained, no study measures it.

In the light of the reviewed literature, the present study contributes to a better understanding of the role of mass public transport projects in Latin American cities in two main aspects: a) It presents a replicable methodology based on rigorous and realistic accessibility metrics to assess the accessibility gap, using open source software and public available data, and b) Models the potential impact of Quito's First Metro Line on accessibility levels and accessibility gap between socioeconomic groups with high detail. These results can inform public debate on high-investment transport projects, and the proposed methodology can be used by planners and decision makers to assess different scenarios for a given project rapidly.

3. Methodology

To determine the impact of the PLMQ on accessibility to urban opportunities, this study follows a quantitative approach, particularly based on spatio-temporal analysis methods. Concretely, the methodology consists of the following phases: i) Characterization of the current level of accessibility of Quito's population to urban opportunities using public transport; ii) Determination of the accessibility gap between socioeconomic groups; iii) Estimation of the impact of the PLMQ's implementation on accessibility levels and on the gap.

3.1. Study area

Quito, the capital of Ecuador, has an area of 266.75Km2. It is located at 2850 m.a.s.l. and has an elongated morphology in a north-south direction with a length-width ratio of approximately 5:1, implying a great challenge for mobility and the spatial distribution of facilities (Guerrero et al., 2020). The study area has been delimited into five zones according to their own functional-spatial relationship and dynamics: south, center, north, hypercenter (which concentrates a large number of economic activities), and Cumbayá-Tumbaco (Fig. 1). The study area's population was 1,852,795 in 2010 (INEC, 2011a). Herein, we will refer to this study area simply as "Quito".

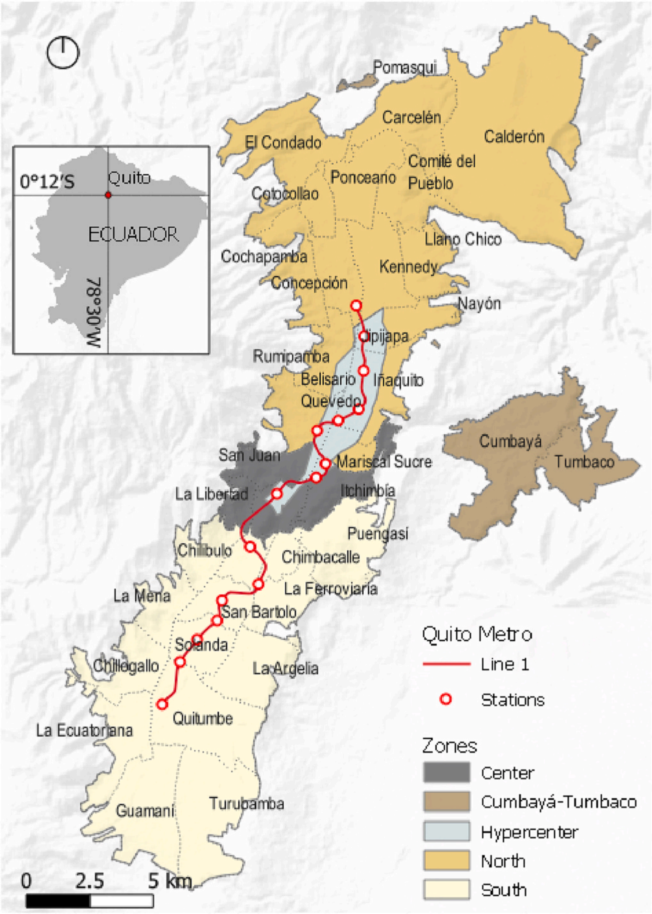


Fig. 1. Quito's study area and zoning. Source: (MDMQ, Municipio del Distrito Metropolitano de Quito, 2021). Cartography: "Authors".

The urban area presents a clear spatial division between north and south, differentiated both by population density and by living conditions. To the north, population density is low and there are better living conditions, while to the south (an area inhabited by 78% of the urban population) living conditions are low and a high population density is concentrated longitudinally. Population density is low in the case of the annexed parishes (Calderón, Cumbayá and Tumbaco). In Calderón, living conditions present relative heterogeneity, tending to the center, a predominance of census sectors with average life conditions, and low in the periphery. Cumbayá and Tumbaco, for their part, show a predominance of census sectors with high living conditions. Fig. 2 presents the differences described regarding the geographical distribution of living conditions and population density.

In the study area there are a total of 8954.07 km of roads. Mobility in the city of Quito is organized based on a public-private transport system. According to Metropolitan Ordinance No. 017–2020 passed for the restructuring of routes and frequencies, 75% of trips are made by public transport and 25% by private transport. The city's public transport system has two subsystems: the conventional bus service and the Metrobus Q, with a total of 3317 units that undertake around 2,874,036 trips in a working day, resulting in 3,698,000 stages (Municipio del Distrito Metropolitano de Quito, 2020).

3.2. Data

This section details the sources and procedures used to obtain and prepare the study's base data. In addition, the scripts in the R Studio language (R Core Team, 2021) are provided as supplementary material to replicate the processes.

3.2.1. Socioeconomic groups

Socioeconomic groups were determined according to the Living Conditions Index (ICV for its acronym in Spanish; Orellana and Osorio, 2014), which synthesizes the level of deprivation or well-being of those who live in a residence through a continuous measure that allows the determination of the inhabitants' living standard of each residence in the city.

The ICV for the population of the study case was calculated using data from the 2010 Population and Housing Census (INEC, 2011b) and incorporates variables related to four dimensions: physical characteristics of the residence (walls and roof materials, in-house facilities), availability of essential inhouse services (drinking water, sanitation, electricity), educational level, and health insurance of household members. The calculation was made for each household in the study area then the ICV scores were assigned to all household members. This process produced a database containing each individual in the study area with its corresponding ICV score and a spatial location assigned from the centroid of the corresponding census tract. The individuals were grouped into quartiles to represent four different socioeconomic groups. The code for the ICV calculation can be found as supplementary material.

3.2.2. Urban opportunities

The data on urban opportunities come from three sources: the Single Metropolitan License for the Exercise of Economic Activities database (LUAE for its acronym in Spanish) with 74,994 points (MDMQ, Municipio del Distrito Metropolitano de Quito, 2020), the Points of Interest database (BID, Banco Interamericano de Desarrollo, 2021) (5544 points), and the Public Spaces database (MDMQ, Municipio del Distrito Metropolitano de Quito, 2018), reviewed and updated in 2019 by the Pontificia Universidad Católica del Ecuador and the Universidad de Cuenca. After a preliminary analysis, the LUAE was chosen as the main source, plus the educational activities from the Points of Interest

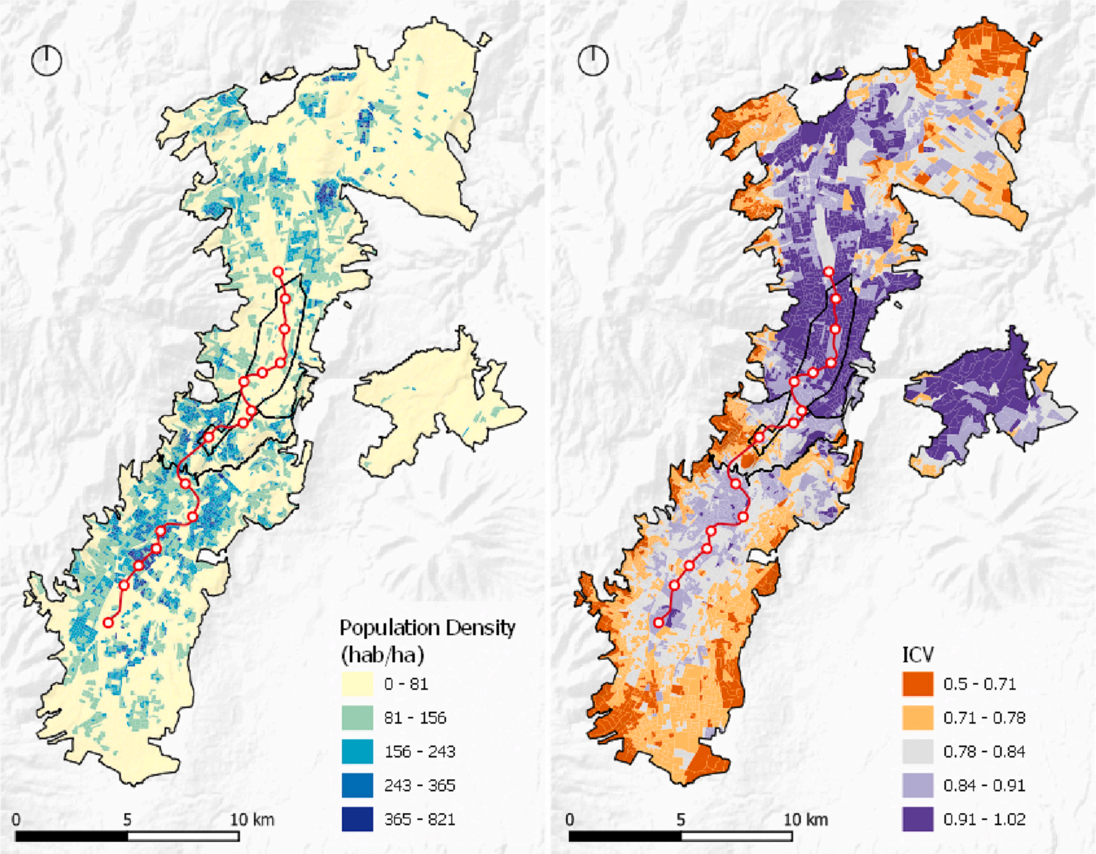


Fig. 2. Population density and mean of the Living Conditions Index (Orellana and Osorio, 2014). Source: Population and Housing Census 2010 (INEC, 2011a). Cartography: "Authors".

database and the Public Spaces data, producing a data set with a total of 77,836 urban opportunities.

Urban opportunities were defined as all land uses different from housing in the city. The unit used for measuring them is each license given by the metropolitan authority for commercial uses or each location of health, education and public space facilities, that later on will be counted with the cumulative opportunities method. An initial rough categorization was made, leaving all small commerce and office locations as Job opportunities, big commerce and industrial locations as Commerce facilities for the population, and Services for health, education and public spaces.

3.2.3. *Public transport*

To characterize the current urban public transport system, information generated by the Secretary of Mobility of the Metropolitan District of Quito was used in GTFS (General Transit Feed Specification) format (MobilityData, 2021). The dataset was georeferenced and included all public transport routes, stops, and schedules including departure time to each stop.

The information was validated using the open source platform GTFS Editor (MobilityData, 2021). During the validation process, errors were found, such as unused stops, duplicate trips, stops far from the geometry of the route, and schedule inconsistencies. These errors were corrected by editing the entities from the GTFS Tools, generating as a result a new corrected version from the GTFS file. The information from Quito's First Metro Line (PLMQ) was added to this file based on the information from Quito's Metro Line Operational Plan, which provided the following data: travel time and length, the geographic information provided by the Secretary of Mobility of the Metropolitan District of Quito in shapefile format with data and location of the metro stations, and geographic information in shapefile format with data and route geometries.

To complete the data regarding times between stations for the trips required in the GTFS specification, an interpolation of travel time over the length of the sections between stations was performed. This information, together with the road network, is later used to compute in-vehicle travel time.

3.2.4. *Travel behavior*

The population's travel behavior parameters, including the number of stages in daily trips, the number of trips in public transport, and travel times were obtained from a survey carried out for the design and planning of the Quito Metro Line, between January and March 2011 with a sample of 77,056 people (Metro Madrid, 2011).

3.3. *Modeling the accessibility level in public transport*

A cumulative opportunities approach was used to determine the population's accessibility level to urban opportunities using public transport. To implement this approach, travel times for realistic travel scenarios between all origins (household locations) and destinations (urban opportunities) must be computed. For single-mode journeys such as walking or driving, these times can be obtained using shortest-path algorithms such as Dijkstra or A-star to compute the shortest route between nodes in a graph (i.e. a street network), using time as impedance (i.e. derived from travel speed on each segment of the network). Travel times can be used to represent isochrones (also known as "service areas"), i.e. the area reachable in a specific amount of time from a point of origin. Similarly, pathfinding algorithms such as RAPTOR (Delling et al., 2021) can be used to compute journeys and travel times on transit networks.

In reality, public transport travel is multimodal, since users must walk from their origin to the closest transport stop and from the last stop to the final destination. Conway et al. (2017) provide a method for rapid and rigorous computation of multi-modal travel times for a matrix of origins and destinations based on the combination and optimization of several algorithms. The method uses a street network from OpenStreetMap and GTFS data to compute optimal routes and travel times for realistic public transit travel behavior. Briefly, the method consists of the following steps: a) search on the street network using a standard Dijkstra algorithm, b) finding transit stops within a reasonable walking distance of the origin, as well as any direct paths to the destination that do not involve transit, c) precompute all possible transfers between stops using the same network and algorithm, d) search the transit network using a variant of RAPTOR (Conway et al., 2017). Moreover, instead of computing a deterministic travel time for each origin-destination pair, the method produces statistics for a set of times for a time-window to account for the real-world variability on the departure and on-stop waiting times. The authors implemented the method in the R5 routing engine and Conveyal Analysis Tool (Conway et al., 2018). These open-source tools allow the calculation of travel times and accessibility indicators, enabling the rapid evaluation and comparison of different scenarios based on realistic travel behavior.

In traditional cumulative opportunities approaches, inherent uncertainties of urban travel behavior are usually excluded, such as the border effect when locations just beyond the cut-off time threshold are excluded underestimating the real world behavior of users who may travel some extra time, or the varying waiting time at transit stops due the natural variation of users' departure schedules that can affect total travel time. To account for the border effect, a distance-decay function can be applied at the isochrone threshold, so opportunities just beyond that threshold are included for the accessibility calculation but with a lower weight than the opportunities that are within it. Also, to include uncertainty for waiting times, Monte Carlo simulations for varying departure times can be implemented, and then using a summary statistics (e.g. median) for further analysis (Conway et al., 2018).

We used Conveyal Analysis to compute isochrones from each point in a 300 m × 300 m regular mesh covering the entire study area. For time intervals of 10 min up to a maximum of 120 min using public transport. This time range would accumulate more than 98% of the trips by public transport in Quito (Metro Madrid S.A., 2011). Then, each isochrone is used to determine the number of reachable urban opportunities from each origin using spatial overlay analysis techniques. As result of this process, a raster spatial layer is produced, representing the local accessibility to urban opportunities for each location in the study area.

Once the accessibility layers are produced, spatial superposition techniques were used again to assign each inhabitant an accessibility value according to their residence location. Thus, it was possible to obtain a detailed data set at the individual level with the place of residence, its Living Conditions Index group, and its accessibility to urban opportunities for times between 10 and 120 min. With these data, the population's accessibility was characterized by means of graphs and statistical summary measures. In particular, representative accessibility percentiles (5, 25, 50, 75 and 95) were studied to have a more thorough view. Accessibility maps were also prepared for each travel time to study the accessibility's spatial and temporal distribution. These processes were implemented in R Software version 1.4.2 (R Core Team, 2016) with the libraries dplyr(), sf(), and raster().

3.4. *Setting the model's parameters and scenarios*

The model to calculate isochrones using the Conveyal Analysis Tool requires setting several parameters, which are detailed below.

The public transport network (buses, trolleybuses, feeders), with their respective routes, stops, and frequencies, were entered according to the Secretary of Mobility's GTFS specification. A maximum of three transfers per trip was allowed to include extreme but realistic scenarios for Quito, where the public transport system includes several feeder subsystems to main lines.

The access mode to public transport was defined on foot, representing the typical behavior of the majority of public transport users in Quito (other options not included in this analysis are access by bicycle or "drop-and-go", that is, a private vehicle leaving a passenger at the corresponding stop). Walking speed in ideal conditions was defined as 5 km/h with impedance factors for different situations: a factor of 2 for slopes greater than 10%, a factor of 1.51 for unpaved streets, and a factor of 1.14 for high-traffic streets (primary and secondary). Additional times of 42.5 s were used for intersections (Conway et al., 2018). The maximum total walking time for a trip was determined to be 60 min to include "worst case" scenarios with little access to public transport. Factors related to traffic intensity were not incorporated due to lack of data, therefore, the impact of congestion is not considered.

One thousand calculation iterations were generated using Monte Carlo simulation with varying departure times to account for the variation in waiting time at the stops, and the isochron was calculated from the 50th percentile of these simulations to obtain a robust statistic for subsequent analyses (Conway et al., 2018). Finally, a logistic decrease function (SD = 10 min) was used to account for the border effect.

The maps' final composition was done in the QGIS 3.18 software (QGIS Developing Team, 2021).

3.5. *Determining the accessibility gap*

To determine the public transport accessibility gap associated with the population's Living Conditions, the spatial accessibility of the population in the Q1 quartile (lowest living conditions) was compared with those in the Q4 quartile (highest living conditions). The difference between the two groups determines the accessibility gap in absolute terms (difference in the number of attainable opportunities), or relative terms (difference divided by Q1's accessibility value). Gap values were calculated for all times and for representative percentiles for each group to produce equivalent comparisons. That is, the gap was calculated by comparing the accessibility of the 50th percentile (median) of the Q1 group with the same percentile of the Q4 group, and in the same way for the other representative percentiles.

3.6. *Estimating PLMQ's impact*

The PLMQ's impact on accessibility to urban opportunities has been estimated by comparing the results of the aforementioned accessibility analyses for two scenarios: a) Baseline, representing the public transport system's current operation system (routes, itineraries, stops, frequencies), and b) PLMQ, representing the PLMQ's launch according to the frequencies proposed in Quito's Metro Line Operational Plan. Impact was calculated as the absolute and relative change between the two scenarios, for each travel time and accessibility percentile, both for the total population and for the accessibility gap. This made it possible to establish to what extent the PLMQ's implementation will impact the population's accessibility and to what extent it will modify the accessibility gap.

4. Results

4.1. *Characterization of accessibility*

Urban opportunities in the study area, especially those related to employment and services, are strongly concentrated in the hypercenter, with a marked decrease towards the peripheries and with underserved areas in the south and in the extreme northeast. It is also interesting to observe a relative scarcity in the parishes of Cumbayá and Tumbaco (Fig. 3 Left). The public transport network also has a heterogeneous distribution with a high concentration of lines and stops in the hypercenter (Fig. 3 Right).

Fig. 4 and Table 1 show the population's current accessibility of the study area. The black line indicates the populations' median

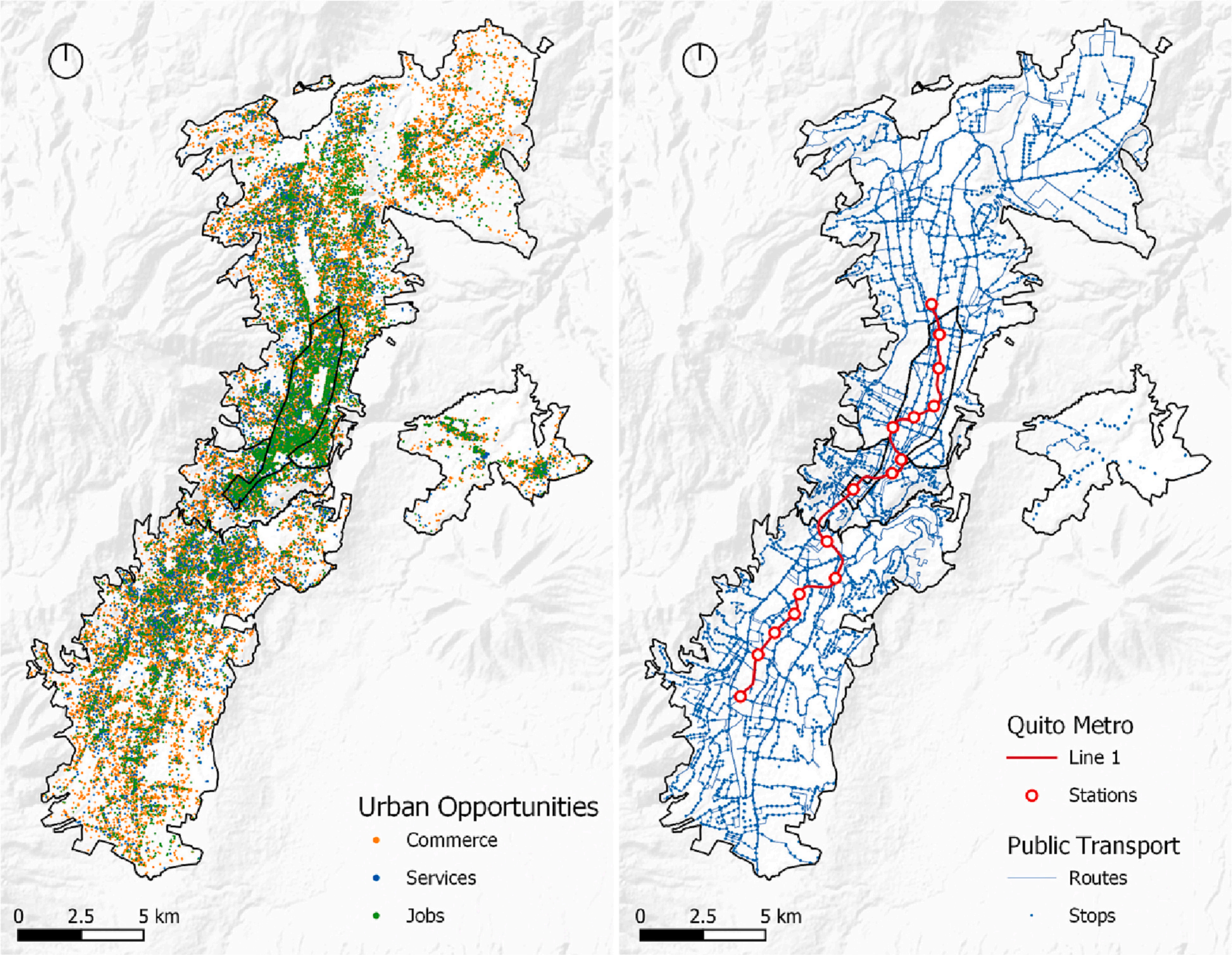


Fig. 3. Left: urban opportunities' spatial distribution of urban opportunities. Right: Public transportation system. Sources: Secretary of Mobility Metropolitan District of Quito, OpenStreetMap. Cartography: "Authors".

accessibility (50th percentile) for time intervals every 10 min. The inner band represents the range between the 25th and 75th percentiles, and the outer band the range between the 5th and 95th percentiles. It is noticeable that accessibility increases considerably after 30 min of travel and then more slowly after 90 min, at which time approximately half the population could access more than 62,000 opportunities. However, the high variability in accessibility is evident. For example, people in the 75th percentile of accessibility can reach 47,000 opportunities in 60 min, while those in the 25th percentile require an additional 20 min to reach a similar number of opportunities. The population in the 5th percentile, with less accessibility, would require almost 100 min to reach an equivalent number.

Accessibility is strongly marked by geographic location. The maps in Fig. 5 show the accessibility values in the study area. For trips of less than 30 min, the effect of the spatial concentration of opportunities in the hypercenter is evident, while after 30 min the public transport system's effect begins to be observed, whose corridors determine the spatial pattern of accessibility. After 90 min, this pattern begins to lose strength since, in that time, almost all urban opportunities can be reached from a large part of the city. This would indicate that the greatest impact of the city's public transport system in terms of accessibility occurs for trips between 30 and 90 min.

4.2. Accessibility gap between social groups

The spatial distribution of the population of group Q1 (with lower living conditions) shows high densities mainly in the city's southern part, in the center's western part, and in the northern outskirts. This group presents an evident exclusion in the hypercenter, the north's central zones, and in Cumbayá and Tumbaco. This distribution strongly differs from that of the Q4 group (with better living conditions), mainly concentrated in the north and the hypercenter, as well as an important presence in the Cumbayá and Tumbaco parishes (Fig. 6). Considering the previous accessibility maps, this spatial distribution gives the first indication of differentiated accessibility to urban opportunities for the two groups.

Fig. 7 represents the population's accessibility of groups Q1 and Q4. It is notable that the curves of the 25th, 50th, and 75th percentiles of the Q4 group are significantly higher than the same curves for the Q1 group, demonstrating the existence of a significant gap between both groups. This difference is especially important between 30 and 80 min, the time in which most of the city's daily trips are found. The specific gap values for the 50th percentile (median) of both groups are presented in Table 2 and Fig. 8; these offer a more complete picture of the accessibility gap. For example, it can be seen that the median accessibility in 30 min for the population of Q1 is 6735 opportunities, while for the population of Q4 is 11,513 in the same time. This represents an absolute difference of 4778 opportunities and a relative difference of 70%. At 60 min the absolute gap is 9005 opportunities (25.5%). As expected, the two median curves converge at the beginning and at the end, indicating that for very short trips (less than 20 min) or very long trips (110 min or more), the accessibility between the two groups does not present an important difference in absolute terms. However, in relative terms, the differences between the two groups are strongly associated with short times, as

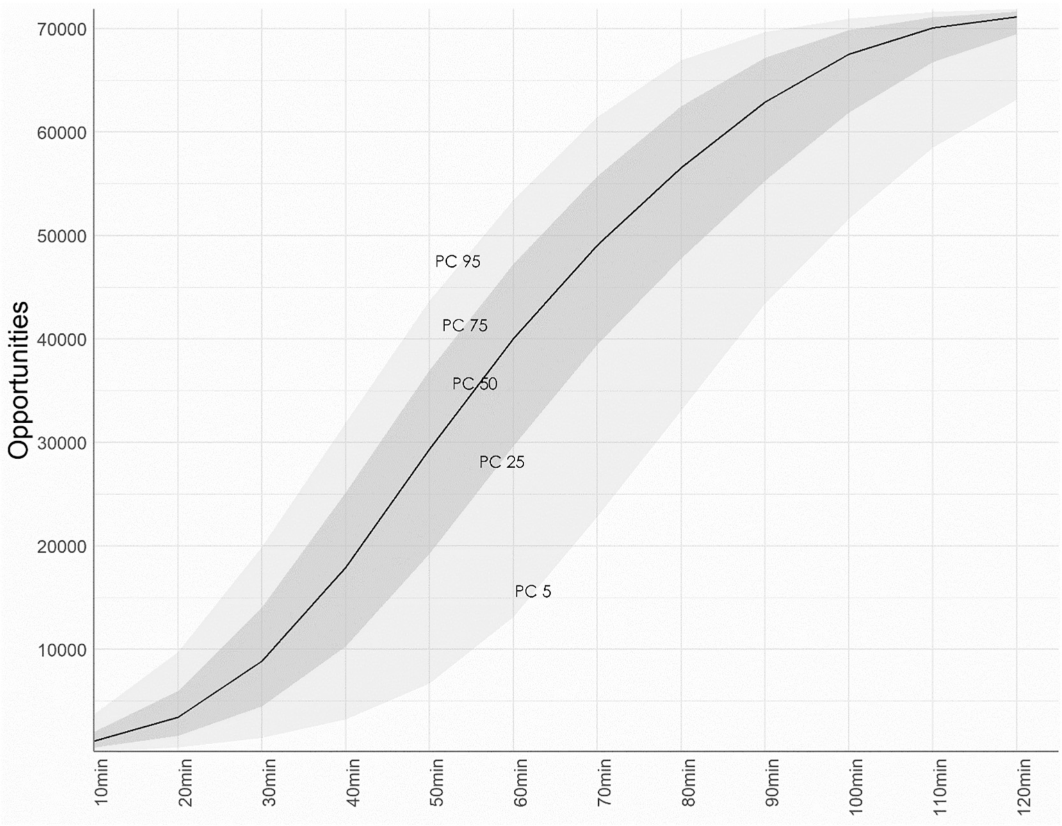


Fig. 4. Population accessibility to urban opportunities in different travel times. Black line = median. Internal band = interval between percentiles 25 and 75 of accessibility, External band = interval between percentiles 5 and 95.

Table 1
Population accessibility percentiles for travel times between 10 and 120 min.

Time (min)	pc05	pc25	pc50	pc75	pc95
10	148	518	1142	2035	3710
20	502	1638	3423	5993	9740
30	1444	4505	8859	14,040	19,887
40	3234	10,311	17,935	25,199	31,921
50	6717	19,248	29,344	36,976	43,672
60	13,142	29,661	40,049	47,245	53,434
70	22,828	39,472	49,065	55,736	61,441
80	33,103	47,799	56,574	62,522	66,927
90	43,405	55,305	62,896	67,176	69,662
100	51,609	61,904	67,517	69,867	70,951
110	58,479	66,774	70,053	71,092	71,602
120	63,124	69,478	71,146	71,649	71,880

shown in the lower section of Fig. 8: The population of Q4 has a median accessibility 92% higher than that of Q1 in 10 min of a trip, and this relative difference declines rapidly up to 60 min, after which the differences decrease more slowly. After 110 min, the relative gap does not exceed 2.5% between the two groups.

In addition to comparing accessibility medians, it is important to look at other percentiles to further explore the gap. Thus, the 25th percentile of the Q1 population accesses 3729 opportunities in 30 min and the same percentile of the Q4 population accesses 6701, which implies a gap of 2972 opportunities (79.7%), In contrast, for the 75th percentile, the gap in 30 min between Q1 and Q4 is 4510 opportunities (39.7%). Interestingly, the differences in accessibility of both groups for the 5th and 95th percentiles are relatively low. This indicates similar accessibility for these population extremes. On the other hand, the wide difference between the 5th and 25th percentiles of the Q4 group, which indicates a great internal variability of accessibility among this group's population should be noted. This could be explained by a strong process of self-segregation in which the wealthiest households choose residential areas far from the city, seeking exclusivity, privacy, and large housing areas, as is the case of urbanizations located in the parishes of Cumbayá and Tumbaco. This population would, therefore, be associated with low accessibility by public transport, but their mobility would be mainly associated with private vehicles.

4.3. *PLMQ's impact on accessibility*

By introducing the PLMQ and keeping the other components of the public transport system unchanged (routes, frequencies, and stations), the population's access to urban opportunities begins to increase significantly from 30 min up to 90 min, time from which the difference between the two scenarios decreases again (Fig. 9).

Although the absolute impact has a similar magnitude for the different percentiles, there is a significant variation in the travel times in which this impact is perceived. Thus, for the 75th and 95th percentiles (those with the highest accessibility), the PLMQ's introduction increases their accessibility between 2000 and 3000 opportunities for travel times between 40 and 70 min. In turn, for the population with the least accessibility (5th and 25th percentiles), the greatest impacts are on long trips, starting at 60 and 80 min, respectively. The greatest absolute impact would be for the 25th percentile in 80-min trips, since this percentile's population will be able to access approximately 3600 additional opportunities in 80 min after the PLMQ's implementation. For the 50th percentile, the strongest impact will be for 50–80 min trips, where they will be able to access more than 2000 additional opportunities (Table 3). In relative terms, the PLMQ would increase the accessibility of all percentiles between 8% and 11%, but this increase will occur in trips of up to 40 min for the population with greater accessibility and in long trips (between 60 and 80 min) for the population with less accessibility.

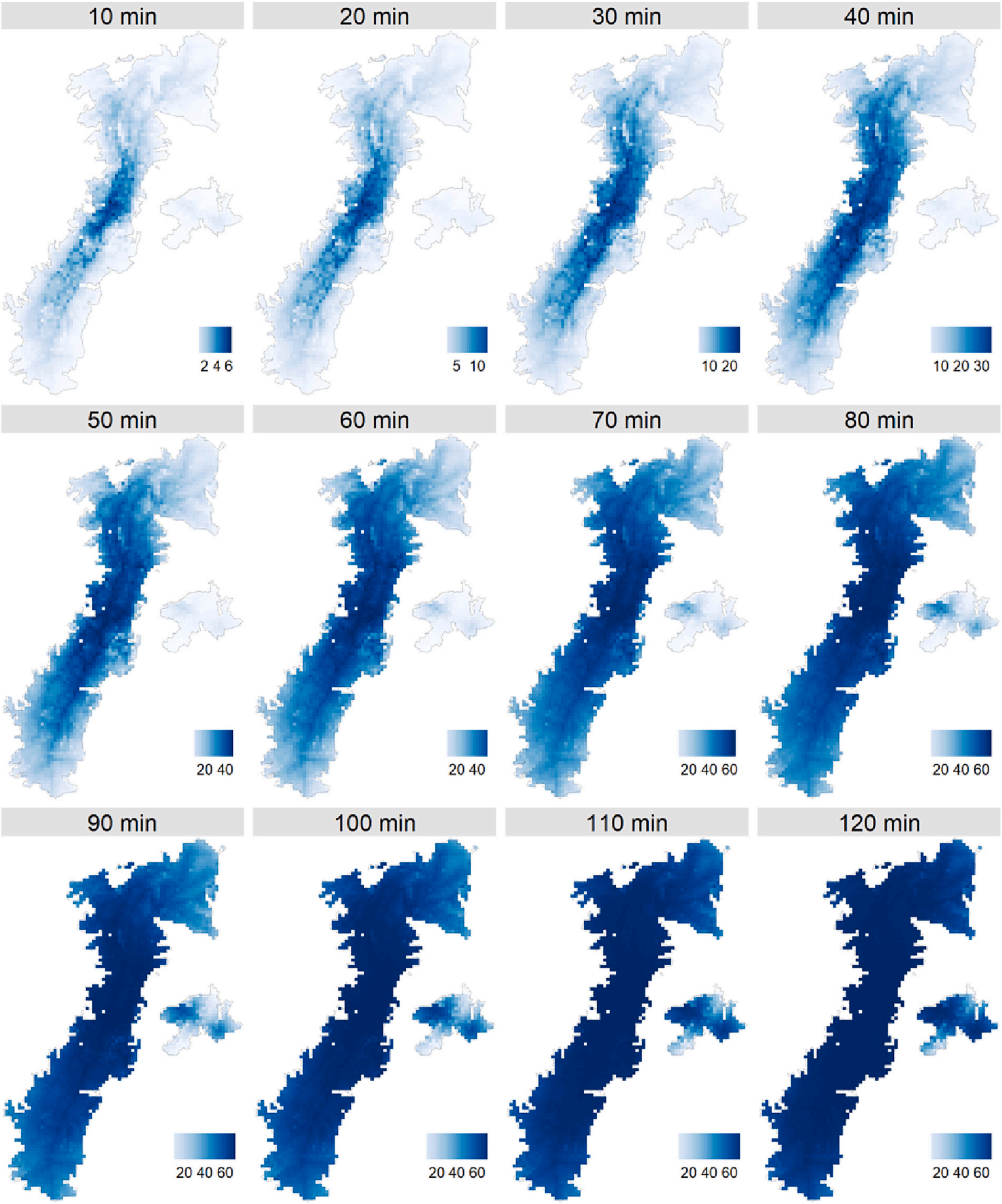


Fig. 5. Maps of spatial accessibility to urban opportunities in different travel times. The legends represent opportunities x 1000. Cartography: "Authors".

Thus, there is a pattern in the PLMQ's impact: it is greater for long trips of the population that currently have little accessibility and for short trips of the population with greater accessibility. On the contrary, the effect is minimal or null for short trips of the population with currently low accessibility and for long trips of the population with high accessibility.

Accessibility impact in space-time terms is represented in the maps of Fig. 10, where it is possible to understand in greater detail its differentiated effect. On short trips of up to 30 min, the greatest relative impact occurs in the vicinity of metro stations, where accessibility can increase by up to 60%. After 50 and 80 min, the differences begin to be more important in the city's southwestern area, whose inhabitants could reach the hypercenter in that time once the PLMQ has been implemented, accessing more than 10,000 additional opportunities, which represents an accessibility increase of up to 30%. The northeastern zone would also begin to have greater accessibility in this time range, with an increase of 200 to 6000 additional opportunities, approximately 10% compared to the baseline.

In general, these results indicate that the PLMQ's implementation will increase accessibility for the majority of Quito's population, but

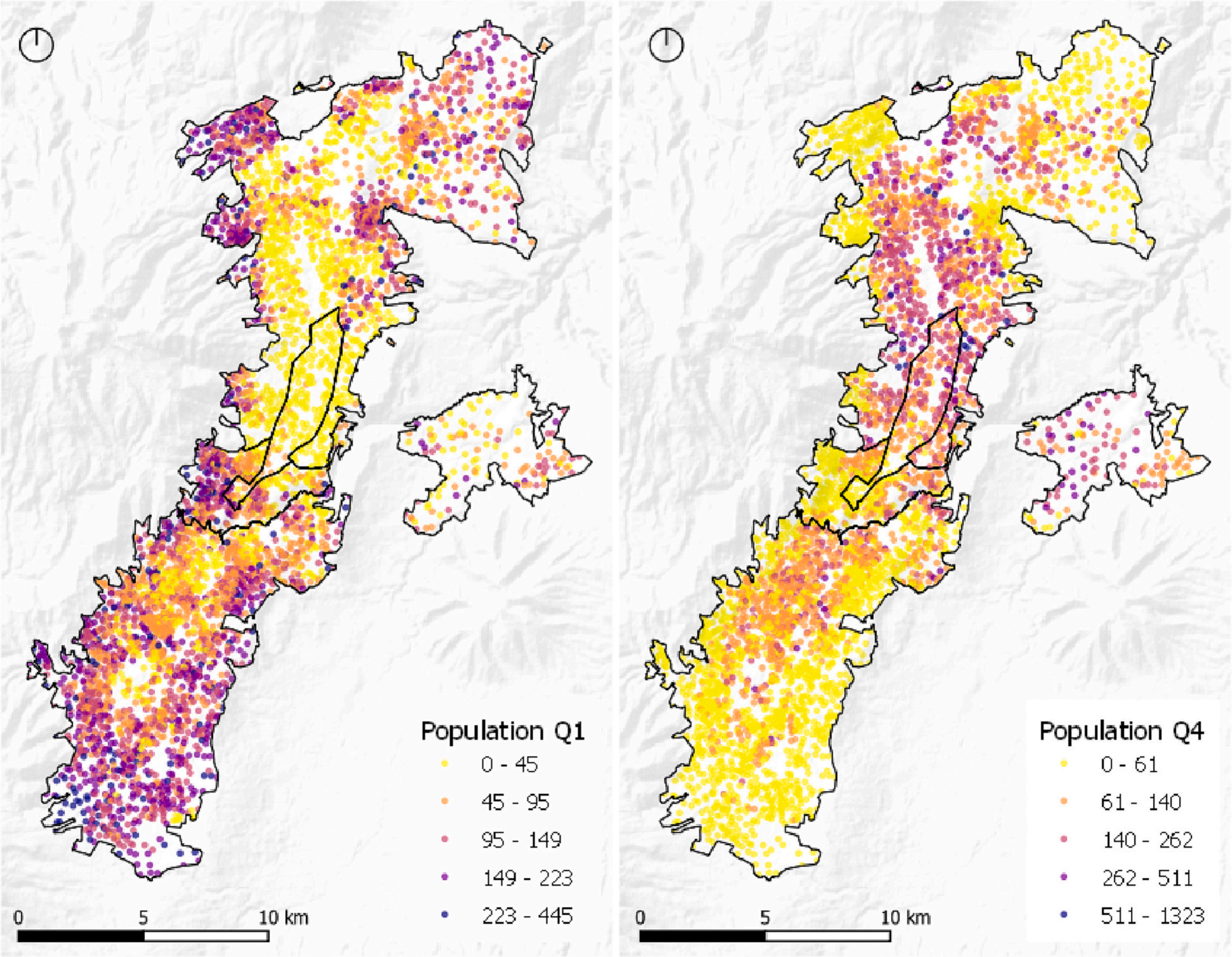


Fig. 6. Population's spatial distribution according to groups of living conditions. Left: Q1, Right: Q4. Source: INEC. Cartography: "Authors".

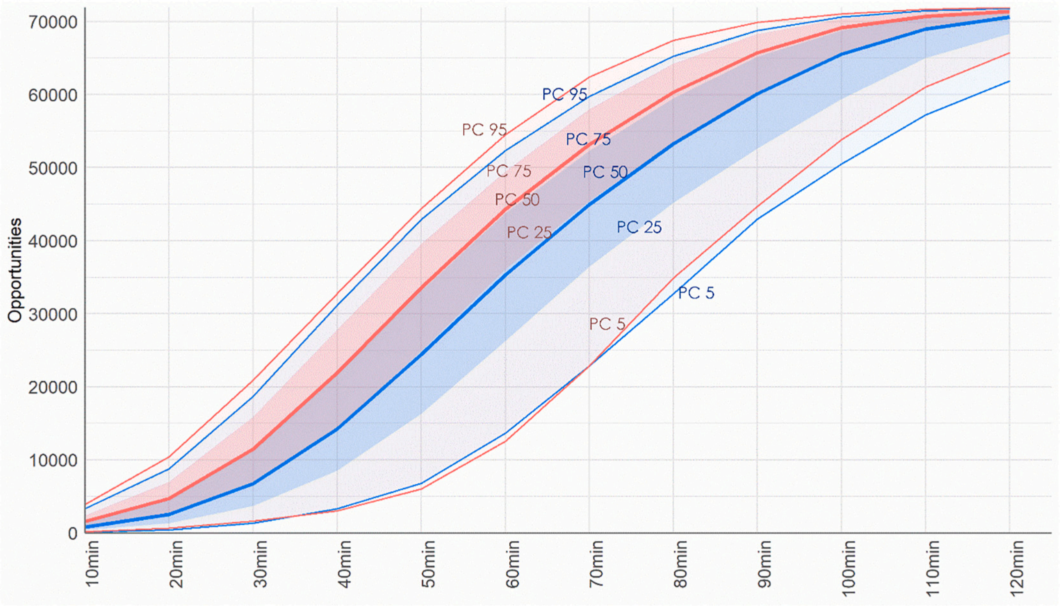


Fig. 7. Accessibility of groups Q1 (Blue) and Q4 (Red) by accessibility percentiles. The thick lines indicate the median, the inner bands the 25th and 75th percentiles, and the outer bands the 5th and 95th percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Current accessibility gap between Q1 and Q4.

Time (min)	Accessibility Q1 (Median)	Accessibility Q4 (Median)	Gap	Relative Gap
10	824	1585	761	0.924
20	2559	4704	2145	0.838
30	6735	11,513	4778	0.709
40	14,236	21,955	7719	0.542
50	24,467	33,563	9096	0.372
60	35,309	44,314	9005	0.255
70	44,944	53,162	8218	0.183
80	53,253	60,307	7054	0.132
90	60,101	65,721	5620	0.094
100	65,522	69,144	3622	0.055
110	68,984	70,724	1740	0.025
120	70,588	71,389	801	0.011

differently. Thus, people residing in highly accessible areas and in the vicinity of Metro stations will see their accessibility increase between 8% and 11% on trips of up to 30 min, while for longer trips, the increase will be less. On the other hand, for the population that currently has low accessibility, generally located in the most peripheral areas, the most significant increases will be approximately 9% in 50-min trips or more, allowing them to access more than 3000 additional opportunities in that time.

4.4. PLMQ's impact on the accessibility gap

When analyzing the changes in the median accessibility for groups Q1 and Q4, it can be observed that in the PLMQ scenario, accessibility increases for both groups after 30 min and especially between 50 and 100 min of travel (Fig. 11). In this time range, the increase is greater for Q1 than for Q4, so the accessibility gap between the groups decreases.

Table 4 and Fig. 12 show the absolute and relative impacts on the accessibility gap for the different times and percentiles. In absolute terms, the most important decrease in the gap occurs in the 5th percentile for 70–80 min trips, where the difference between groups Q1 and Q4 decreases between 960 and 1620 opportunities, that is, a gap reduction between 4% and 5%. It can also be seen that for the 25th and 75th percentiles the gap increases in short trips; in other words, in those specific cases, the PLMQ's benefit is greater for the Q4 group than for the Q1 group. However, after 50 min, the gap tends to decrease for all percentiles. Based on this evidence, it is possible to affirm that the PLMQ will have a positive impact, not only in increasing accessibility to urban opportunities for the majority of the population, but also in reducing the accessibility gap between the population with higher and lower living conditions. However, this impact varies strongly according to the population's geographic location and, consequently, travel time.

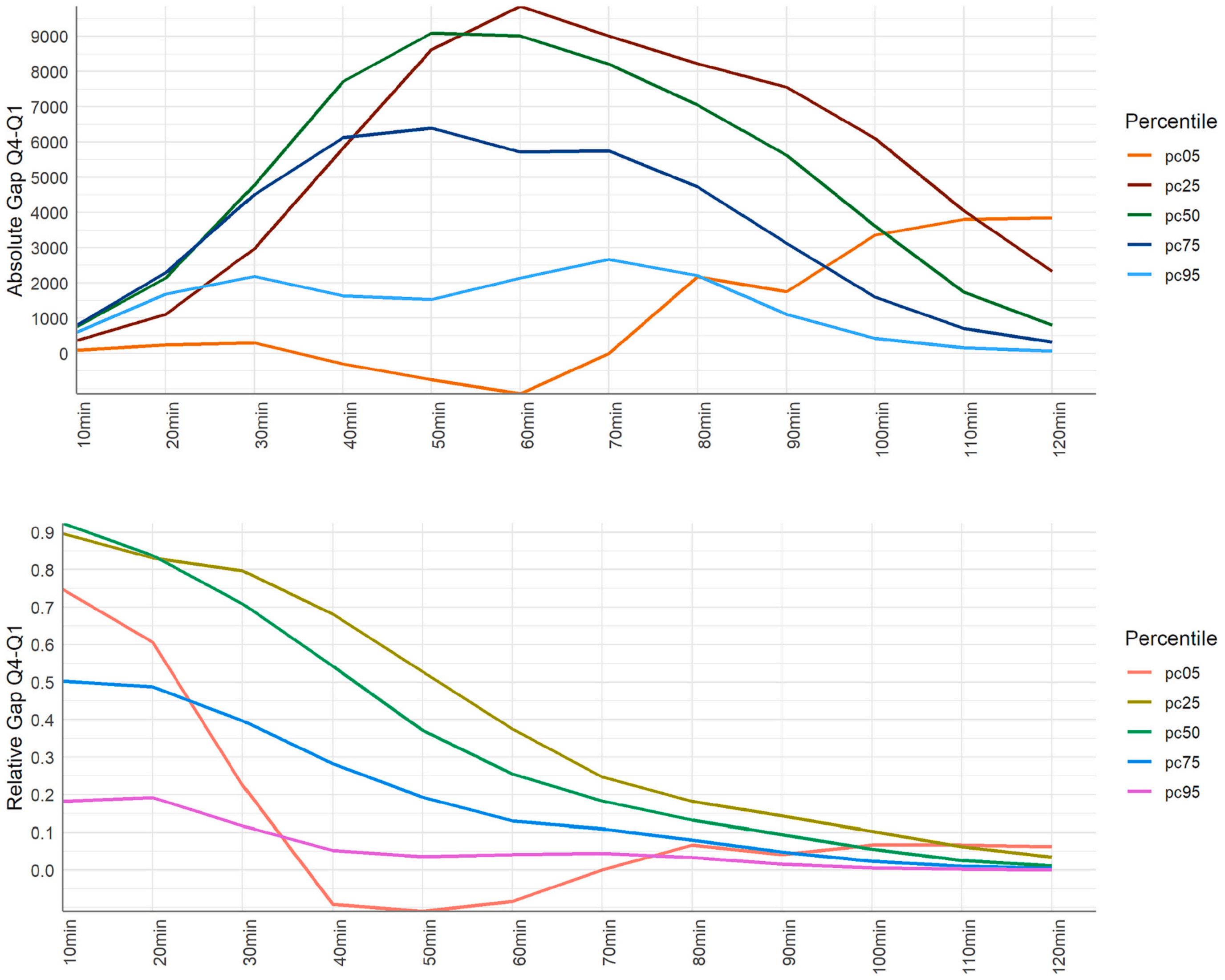


Fig. 8. Accessibility gap between the medians of groups Q1 and Q4. Above: Absolute Gap. Bottom: Relative gap.

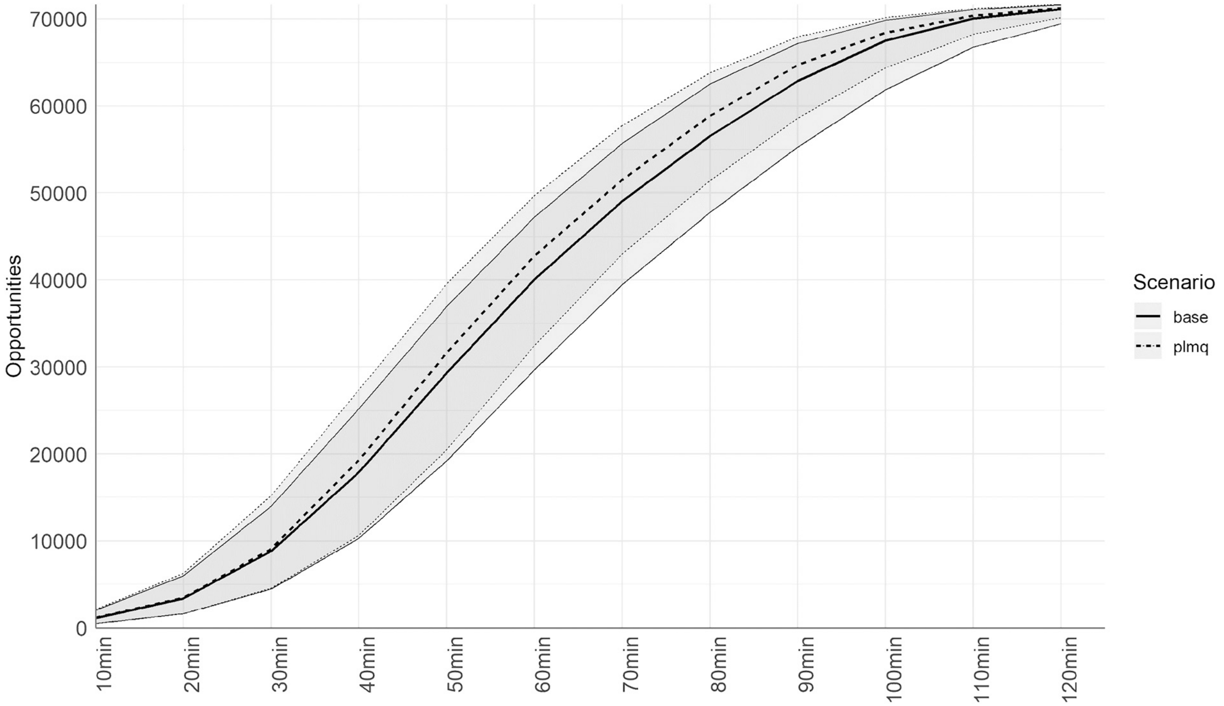
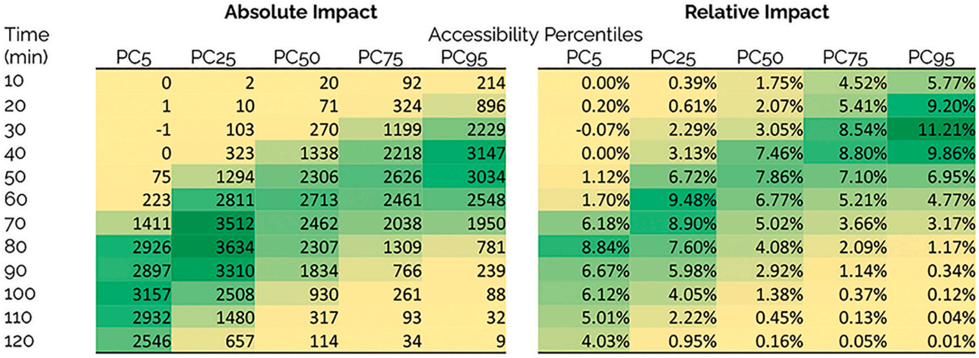


Fig. 9. Population's accessibility in the baseline (continuous line) and PLMQ (dotted line) scenarios. The thick lines represent the 50th percentile and the gray bands represent the 25th and 75th percentiles.

Table 3
PLMQ's Impact on accessibility by percentiles and travel times.



Time (min)	Absolute Impact					Relative Impact				
	Accessibility Percentiles									
	PC5	PC25	PC50	PC75	PC95	PC5	PC25	PC50	PC75	PC95
10	0	2	20	92	214	0.00%	0.39%	1.75%	4.52%	5.77%
20	1	10	71	324	896	0.20%	0.61%	2.07%	5.41%	9.20%
30	-1	103	270	1199	2229	-0.07%	2.29%	3.05%	8.54%	11.21%
40	0	323	1338	2218	3147	0.00%	3.13%	7.46%	8.80%	9.86%
50	75	1294	2306	2626	3034	1.12%	6.72%	7.86%	7.10%	6.95%
60	223	2811	2713	2461	2548	1.70%	9.48%	6.77%	5.21%	4.77%
70	1411	3512	2462	2038	1950	6.18%	8.90%	5.02%	3.66%	3.17%
80	2926	3634	2307	1309	781	8.84%	7.60%	4.08%	2.09%	1.17%
90	2897	3310	1834	766	239	6.67%	5.98%	2.92%	1.14%	0.34%
100	3157	2508	930	261	88	6.12%	4.05%	1.38%	0.37%	0.12%
110	2932	1480	317	93	32	5.01%	2.22%	0.45%	0.13%	0.04%
120	2546	657	114	34	9	4.03%	0.95%	0.16%	0.05%	0.01%

5. Discussion

Currently, Quito's accessibility level to urban opportunities presents a high variability among the study area's population. As has been shown, in trips between 30 and 90 min in the current public transport system, most of the population reaches the majority of urban opportunities. While for trips of less than 30 min, accessibility is low for an important population segment. This dynamic is also reflected in socioeconomic groups. In short trips, the Q4 population (with better living conditions) presents 90% greater accessibility (relative gap) in relation to the Q1 population (with lower living conditions). It is evident that the population with less accessibility and poorer living conditions needs longer trips on public transport to access urban opportunities.

This dynamic responds to the population's spatial distribution in the study area. Similar to other Latin American capitals, Quito presents a condition of socioeconomic exclusion expressed in large spatial consolidations (Bonilla Mena, 2016). The greatest population density and the population with the lowest living conditions are concentrated in the least served zones of the study area: to the south, northeast, and the periphery.

On the other hand, the population with better living conditions is located in the hypercenter, near the area with the highest concentration of jobs, services, stops, and lines of the public transport system. These conditions perpetuate the accessibility gap between socioeconomic groups. There are exceptions, such as the case of several residences with better living conditions, self-segregated in Cumbayá and Tumbaco. Their accessibility is very low in relation to public transport, which determines the use of private vehicles as their main means of transportation, especially to access Quito's hypercenter.

Regarding the impact the PLMQ's implementation would have on accessibility, the entire population will improve their condition, as shown earlier, but differently. According to the population's current accessibility levels, their living conditions, and their location in the study area, the increase in accessibility occurs at different travel times. The population with greater accessibility now will significantly increase their accessibility to opportunities in relatively short trips (40 min),

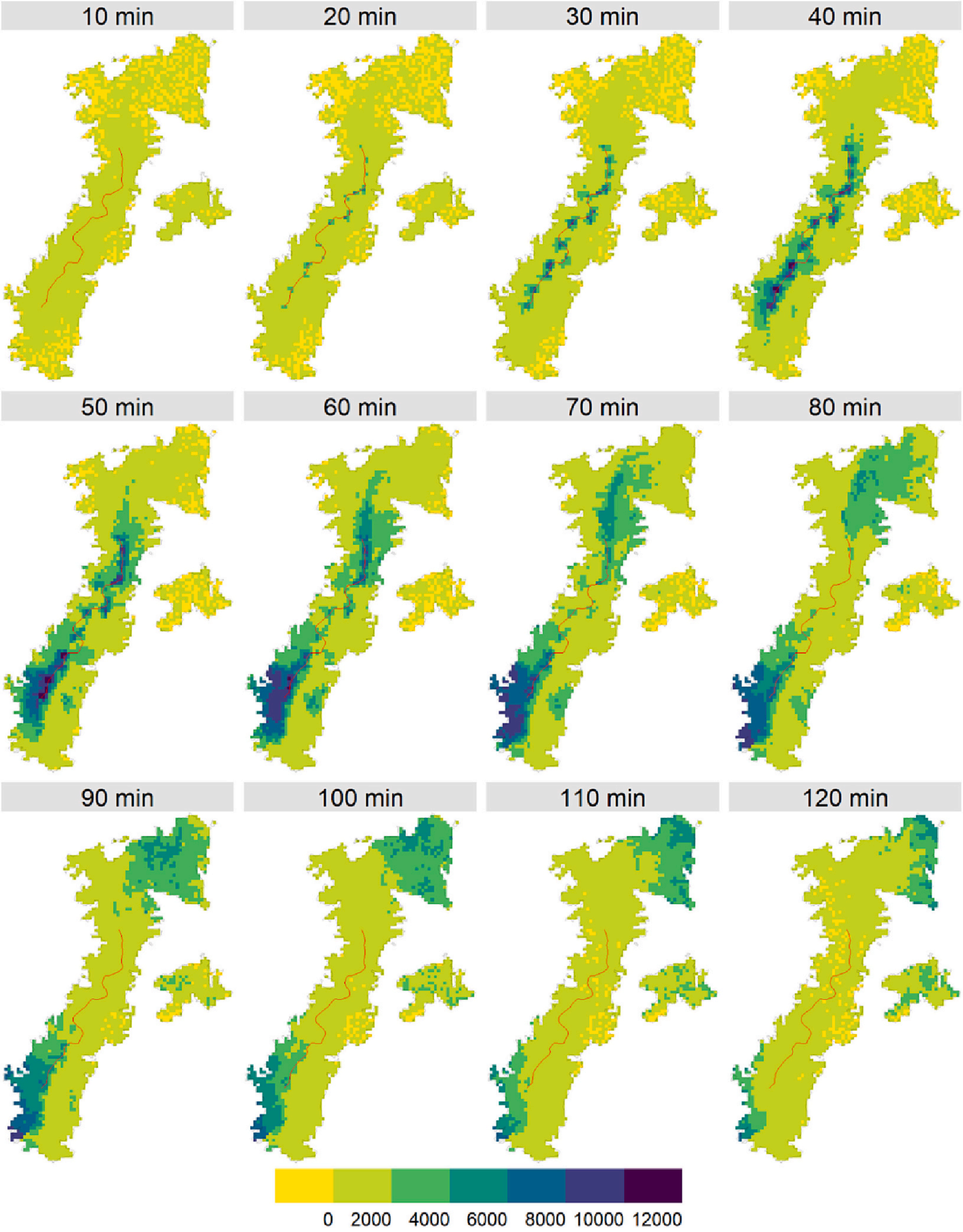


Fig. 10. PLMQ's spatial and temporal impact on the population's accessibility (medians). Cartography: "Authors".

while people who currently have less accessibility will gain an increase when making longer trips (60 to 80 min).

From a territorial point of view, the increased accessibility in neighborhoods to the north and south enables these areas' inhabitants to access job opportunities in Quito's hypercenter. In contrast, the results show a low limited accessibility increase in opportunities in the southeast area. Thus, it is necessary to strengthen or prioritize the distribution of public transport routes and feeder frequencies in these areas. In general, and after analyzing the results, an important difference is highlighted in the southeast and northwest areas of the city.

This general improvement in accessibility has specificities when the difference between socioeconomic groups is reviewed. As explained previously, Q4 has higher accessibility than Q1. This gap increases for short trips since a large part of Q4 is located near PLMQ stations. However, when we consider long trips (between 70 and 80 min), the gap is reduced to a 5% difference between Q4 and Q1. Accessibility increases for areas far from the Metro route both to the north and to the south.

The analysis of times and accessibility to urban opportunities can be significantly modified if we consider the complementarity that the PLMQ could achieve with an adequate feeder subsystem, which allows people to reach that last step that separates them from urban opportunities. This accessibility can improve social integration, especially of vulnerable people (age, gender, poverty, disability, or others). As other experiences worldwide indicate, improving mobility conditions through the implementation of mass public transport systems implies the need to complement this infrastructure with an adequate feeder network, which incorporates an optimum pedestrian and bicycle system, and other means of transport that promote intermodality. In addition, land use planning, (commerce, industry, housing and others) plays a key role in the decentralization of urban opportunities in order to reduce the time

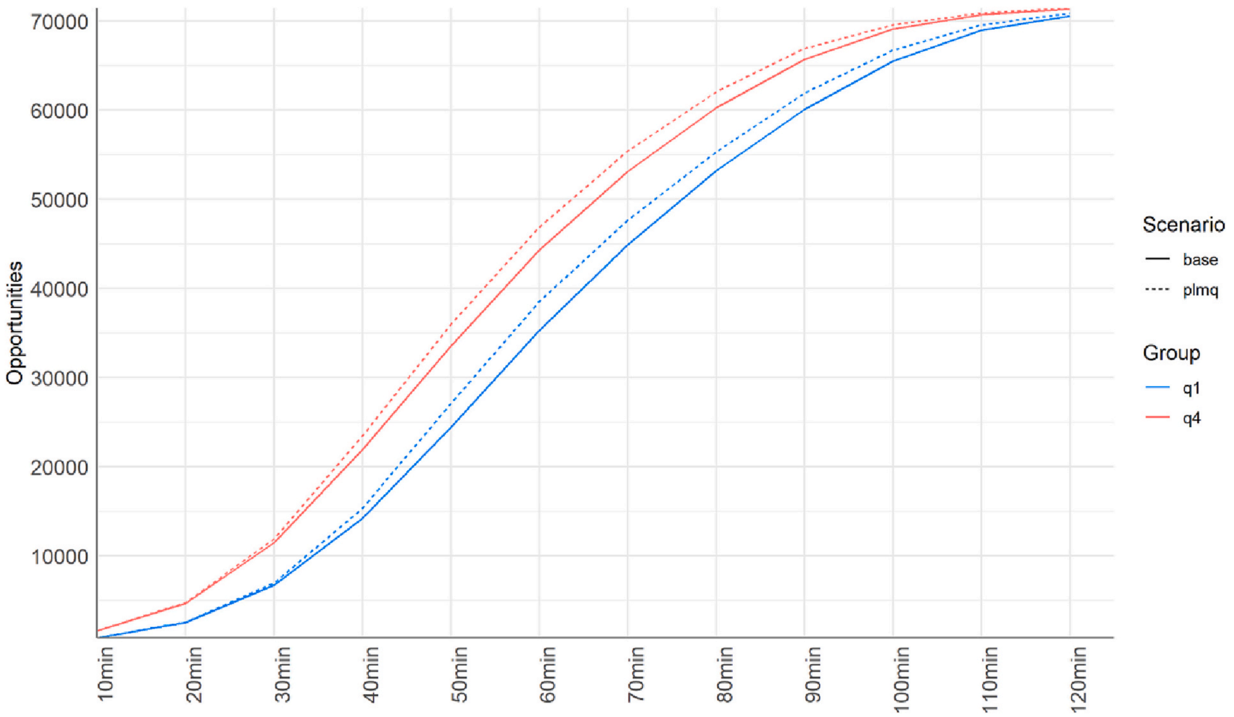
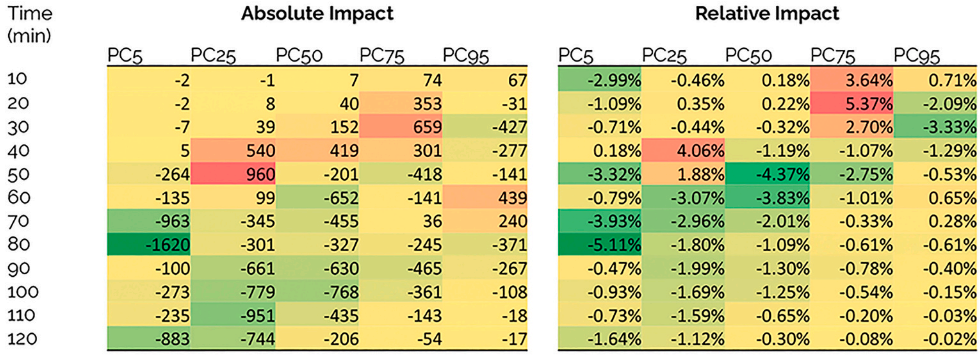


Fig. 11. Changes in accessibility to opportunities for the population's median of groups Q1 and Q4 in the Baseline and PLMQ scenarios.

Table 4
PLMQ's impact on the accessibility gap by percentiles and travel time.



Time (min)	Absolute Impact					Relative Impact				
	PC5	PC25	PC50	PC75	PC95	PC5	PC25	PC50	PC75	PC95
10	-2	-1	7	74	67	-2.99%	-0.46%	0.18%	3.64%	0.71%
20	-2	8	40	353	-31	-1.09%	0.35%	0.22%	5.37%	-2.09%
30	-7	39	152	659	-427	-0.71%	-0.44%	-0.32%	2.70%	-3.33%
40	5	540	419	301	-277	0.18%	4.06%	-1.19%	-1.07%	-1.29%
50	-264	960	-201	-418	-141	-3.32%	1.88%	-4.37%	-2.75%	-0.53%
60	-135	99	-652	-141	439	-0.79%	-3.07%	-3.83%	-1.01%	0.65%
70	-963	-345	-455	36	240	-3.93%	-2.96%	-2.01%	-0.33%	0.28%
80	-1620	-301	-327	-245	-371	-5.11%	-1.80%	-1.09%	-0.61%	-0.61%
90	-100	-661	-630	-465	-267	-0.47%	-1.99%	-1.30%	-0.78%	-0.40%
100	-273	-779	-768	-361	-108	-0.93%	-1.69%	-1.25%	-0.54%	-0.15%
110	-235	-951	-435	-143	-18	-0.73%	-1.59%	-0.65%	-0.20%	-0.03%
120	-883	-744	-206	-54	-17	-1.64%	-1.12%	-0.30%	-0.08%	-0.02%

and costs the population currently invest in their mobility, and the environmental impacts produced by the excessive use of private vehicles (Guzman et al., 2018; Yáñez-Pagans et al., 2018; Costa et al., 2021; M. Liu et al., 2021;).

6. Conclusions

This study analyzes the possible impact of the operation of Quito's First Metro Line (PLMQ) on accessibility to urban opportunities and on the accessibility gap between different socioeconomic groups in the city. This analysis has been undertaken within the framework of the levels of social inclusion and exclusion related to public transport and focused on the spatial and temporal dimension of the measurement of accessibility. The results show that the PLMQ's implementation will increase accessibility to urban opportunities and reduce the existing gap between socioeconomic groups of lower and higher living conditions. However, this impact is highly variable depending on the population's place of residence and users' public transportation travel time. In addition, there are zones of the study area that require greater attention in urban planning to improve their accessibility conditions. The study has also presented a robust and replicable methodology to evaluate public transport projects even in their earliest planning stages. These results contribute to informing planning and public debate on high-investment transport projects.

It is worth noting that this study focused on analyzing how public transport allows the population to access urban opportunities regardless of its behavior and individual preferences in terms of travel modes and destinations. Thus, the accessibility gap analyzed refers only to public transport. We recommend that future studies explore this gap by incorporating the means of transport associated with households from the different socio-economic groups, for which detailed data on vehicle availability would be needed. Additionally, this study does not include the restructuring of the current public transport lines for the PLMQ scenario since the necessary information is not yet available in the GTFS specification. For this reason, in the following steps of this research, the inclusion of said modifications should be considered to evaluate this third scenario. Finally, since the proposed approach privileged simplicity and replicability, it does not include several factors that might

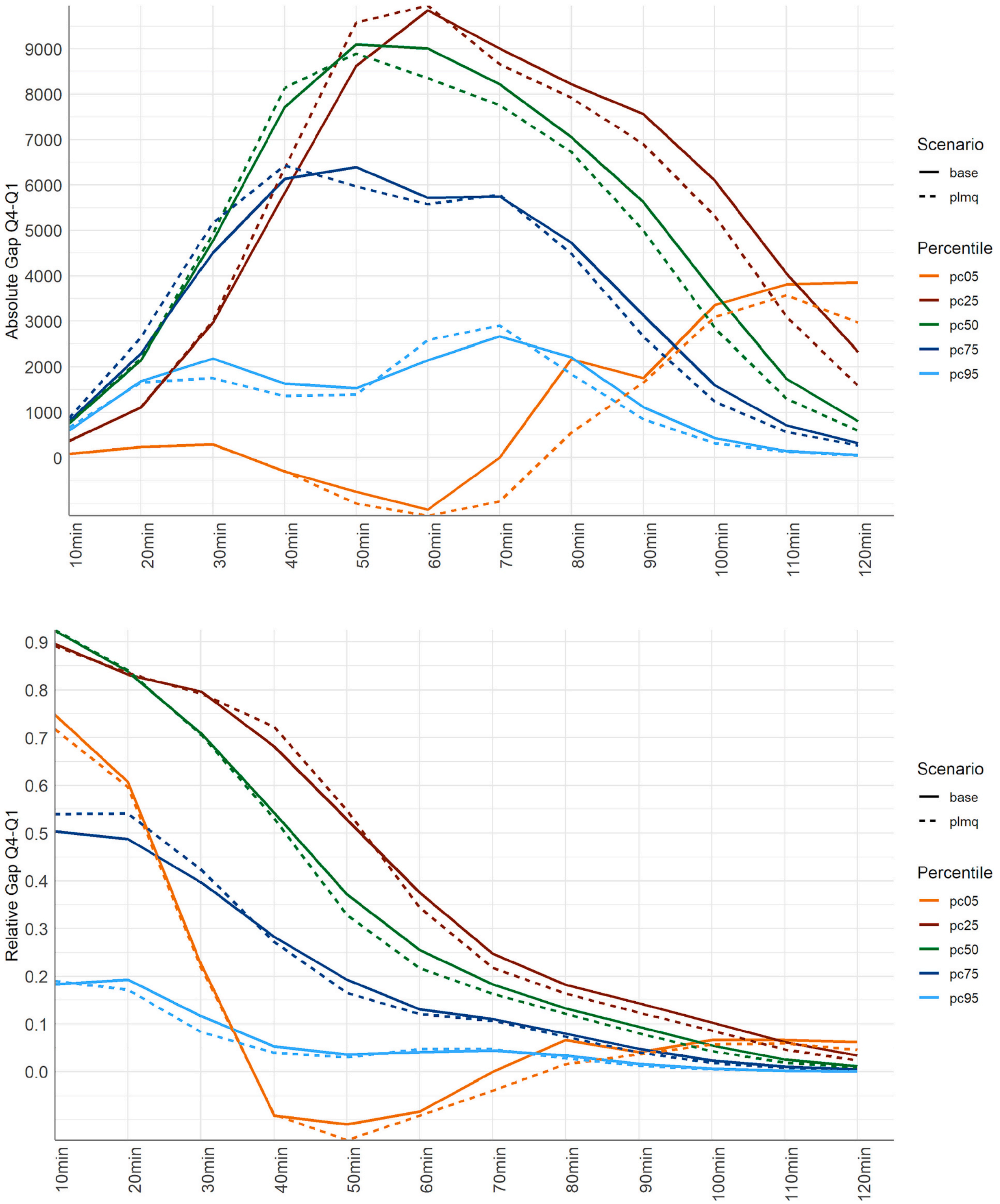


Fig. 12. Changes in the accessibility gap between the Baseline and PLMQ scenarios for different percentiles. Above: Absolute gap. Bottom: Relative gap.

affect accessibility metrics, such as traffic congestion, service demand, system capacity, impacts on land use, or accessibility to specific urban opportunities. Therefore, it lays a solid foundation to explore these aspects in future research to expand the methodology to a "dynamic" accessibility gap that responds to changes on the environment and varies across time depending on travel behavior patterns. As Conway et al. (2017) argue, this kind of approaches allows immediate feedback during early-stages of transit planning, while being rigorous enough for final analyses.

The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of the Inter-American Development Bank.

Declaration of Competing Interest

The Inter-American Development Bank IDB founded this research, and is also investor of the "Metro de Quito" project. The study's authors have no affiliation with IDB, Municipality of Quito, or Empresa Pública Metropolitana Metro de Quito and therefore declare no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtrangeo.2023.103548.

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