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A COMPARATIVE ANALYSIS, THROUGH GEOGRAPHICAL ACCESSIBILITY, OF URBAN PUBLIC TRANSPORT SYSTEMS IN CITIES OF COLOMBIA'S COFFEE-GROWING REGION

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Abstract: Valuing urban public transport plays a vital role in the growth and development of a city. In addition, an exemplary system connection allows the formation of functional relationships between the different users and the surrounding environment. That is why, in this research, it is proposed as an objective to carry out a comparative analysis of the levels of coverage offered by Public Transport Systems in cities of the Colombian coffee region to visualize the current state of operation of each city. The research methodology uses geographic accessibility as a visualization tool complemented with the analysis of sociodemographic coverage. The main result is that the assessment of accessibility and coverage shows that the population has easy access in a travel time of less than 35 minutes. It can also be concluded that the evaluation process provides a broad view of the levels of transport supply in each city.

Keywords: accessibility, public transportation, coffee-growing region, GIS

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INTRODUCTION

Urban public transport systems play an essential role in the growth and development of current cities (Murray, 2003; Jhonson, 2023), allowing the population to move throughout the city without the need to use private vehicles, connecting residential areas with primary activity nodes, reducing congestion levels, pollution (Delmelle et al., 2012; Tribby and Zandbergen, 2012), social exclusion, access to various areas of the city (García et al., 2023), among others (Lucas, 2012; Miralles and Cebollada, 2003). However, despite their benefits, public transport systems also have operational shortcomings and drawbacks, which affect users, such as over-supply of routes, age of the vehicle fleet, and the high number of stops along the route. Although, it would be thought to increase availability and ease of access, increase the travel time of users (Gibson et al., 1989), reducing service levels. These shortcomings generate the need to evaluate the coverage and quality of the service, thus allowing the development of various evaluation methods, some focused on demand analysis and others through supply analysis (Gleason, 1975; Montoya, 2019).

Within these methodologies for evaluating the supply of transport systems, we have the geographical accessibility model, where the cost of travel is determined within a graphical environment consisting of nodes and arcs, representing the functioning of users' travel conditions of public transport vehicles. This concept refers to the possibility or ease of access to a place. However, it has been described and used since 1959 as the potential for interaction opportunites (Hansen, 1959), based on the use of an available mode of transport and the existing limitations to achieve it (Dalvi and Martin, 1976; Morris et al., 1994). Although very general, this definition allows the identification of some critical components for assessing accessibility, such as the modes of transport available and the means or infrastructure on which users move. Components that, when abstracted from reality, can be interpreted or visualized through the application of graph theory (Tutte, 2001), thus providing a greater capacity for analysis with a low development cost concerning a full-scale simulation.

On the other hand, there are several methods within the accessibility measures and the existing process inputs. Some of them are the Average Integral Accessibility Method, which relates the ease of access from or to a particular point of interest based on the users' displacement of a system in any surrounding place (Handy and Niemeier, 1997; Pirie, 1979) and the Geographic Accessibility Method, where the existing interaction of each stakeholder in the analyzed environment is evaluated, identifying the average cost of travel according to the mode of transport used. On the other hand, accessibility

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estimation methods do not include displacement parameters but the availability of services and population requirements. Thus, there are some assessments, such as the 2SFCA (Two-step float catchment area) and the E2SFCA (Enhanced Two-step float catchment area) (Chen and Jia, 2019; Luo and Qi, 2009), where the valuation of potential access to services is made possible, depending on the available supply, and the catchment area of users who could access the service.

Although there are many more accessibility assessments, each allows the interpretation of potential interaction established by Hansen independently of the mode by which it is evaluated. Therefore, the actual diversity of accessibility analysis has allowed the application of the methods in different fields of science, such as health (Ulak et al., 2017), economics (Montoya et al., 2017), planning (Abley et al., 2013), education (Escobar et al., 2017), transport (Geurs, 2004) and many other topics in modern cities. Given the above, accessibility measurements can be considered a robust tool for evaluating and planning a city for the future due to the relatively easy way of incorporating modifications and measuring the impact on society, making it a suitable method for evaluating and comparing public transport systems in different cities.

This research aims to evaluate the differences in coverage in the provision of public transport services in the three main cities of the Colombian coffee region, measuring their capacities through the application of accessibility measures and geostatistical models combined with socio-demographic analysis to diagnose the current service state and the population affected. The Colombian coffee-growing region, located in the center of the country (Figure 1), corresponding to 19834 km^2 (Orjuela et al., 2020) covering the departments of Caldas, Risaralda, Quindío, and Norte del Valle del Cauca, is used as a focus of the study. A region whose main economic activity, since the last century and even today, is based on the production of export-quality coffee. This product identifies Colombia in the world. In addition, the United Nations (UN) declared the coffee cultural landscape a World Heritage Site in 2011, a fact that stands out the area and, at the same time, encourages its care and projection as a tourist attraction.

This territory, shaped and structured since colonial times, when coffee cultivation processes began, has as its main cities and focal points of economic development the capitals of the departments of Caldas, Risaralda, and Quindío - Manizales, Pereira and Armenia-, on which this research focuses. They have a population of 457,022, 482,483, and 309,474 inhabitants, according to the latest national census by the National Administrative Department of Statistics (DANE, 2024). Manizales is located at an altitude of 2150 meters above sea level, with an urban extension in mountainous terrain with a broken and abrupt topography that forces the implementation of alternative modes of transport to the typical passenger bus. Manizales has implemented aerial cable lines to improve public transport capacity and has intended to create a whole network in the future so that it is possible to connect with a high percentage of the city through this mode of clean transport. Currently, eight public transport companies that provide the service in semi-buses, buses, vans, or minibuses (Alcaldía de Manizales, 2017) complement the cable network, the ones that are not integrated into the system, forcing individual payment of fares, generating intermodal competition.

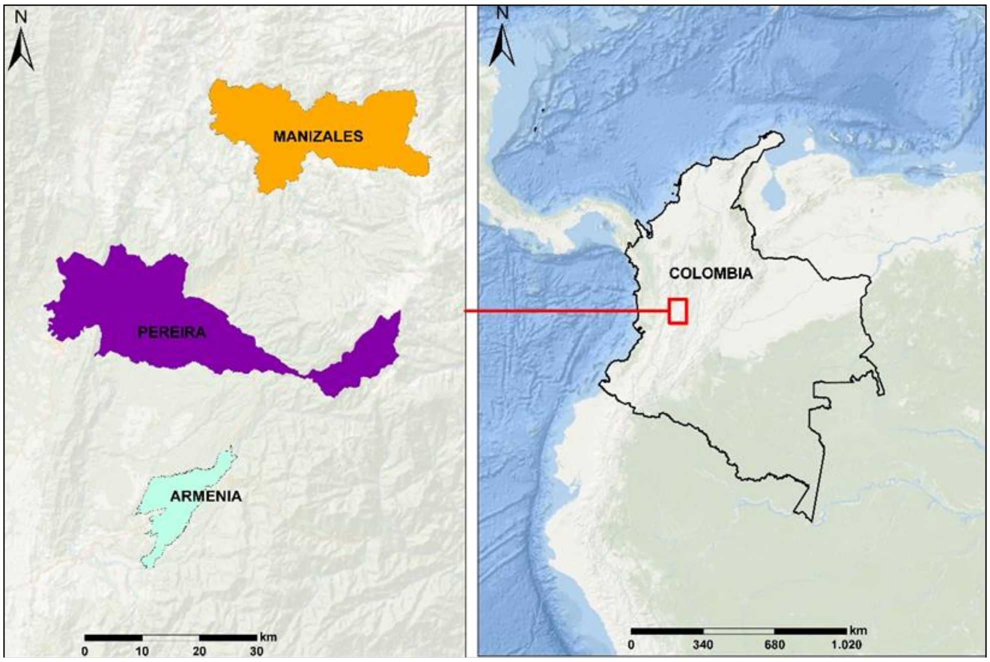

Figure 1. Cities in the Colombian coffee-growing region (Source: Authors)

On the other hand, Pereira, located at 1411 m a.s.l. in the valley of the Otún River in the Central Cordillera of the Colombian Andes, has a public transportation service that is physically and fares integrated under the name of MEGABUS with 148 routes in exclusive lanes on the main arteries of the city, complemented by feeder routes, associated with the company Lineas Pereiranas S.A., linking operations to the municipality of Dosquebradas and La Virginia as a single urban core (Megabus, 2022). The analysis of the accessibility to the Pereira-Dosquebradas integration is carried out.

Finally, the municipality of Armenia is located at 1480 m a.s.l. and has the smallest area among the capitals under study. Public transport operates thanks to a Strategic Public Transport System (SETP) implemented by the mayor's office through "Amable," an industrial and commercial state company created to develop this purpose. The SETP works with 34 routes with pre-existing public service companies through a system of rechargeable cards (Amable, 2022)

MATERIALS AND METHODS

The methodological structure used, Figure 2, has a total of 4 stages, starting with the data collection, in which the current information is reviewed, continuing with the structuring and review of data, where the status of the inputs is verified. The measures of accessibility and coverage are established to structure the results obtained from the analysis. Each stage used in the methodology operates sequentially and is described below.

Phase 1 – Data Collection: The first requirement for the analysis construction is to collect the essential information associated with the cities of study. Thus, the infrastructure networks of urban public transport, municipal urban boundaries, population polygons, and socio-economic stratification, defined by DANE as the population's economic capacity classification in groups from 1 to 6, where the population with the lowest purchasing power will be in the lowest scale and people with the highest purchasing power in the scale number 6 (DANE, 2022), this classification allows the national administration to determine the costs of public services and/or subsidies for the population, thus providing greater equity to the population according to their needs. The initial information base is obtained from previous research carried out, considering the previous process of construction and evaluation of each infrastructure network existing in the databases of Universidad Nacional de Colombia, Manizales.

Phase 2 – Structuring and optimising modelling networks: The following methodological item is the structuring and optimization of the different public transport modeling networks to be used in the analysis, based on the application of graph theory (Tutte, 2001), where the transport supply is characterized through the use of nodes and arcs, associated with the system's physical and operational properties (speed, directionality, length, Etc.).

The information related to the road infrastructure comes from different administrative entities, which are included in the developed mobility plans. Regarding the physical characteristics (directionality and length), the existing structure is considered, verifying its condition through Google Maps and/or OpenStreetMap, in search of irregularities compared to the current condition. Regarding the operating speed, the value established by the service providers is linked, as they constantly monitor the system's operability. However, in road corridors where public transportation vehicles do not circulate, walking speed (4.32 km/h) is considered as the standard operating value in the network. It is important to note that, despite having mixed-use systems in operation, congestion conditions are not directly linked, considering that the speed collection by the operators is in real-time, and therefore already indirectly included in the analysis.

The process considers using geographic information tools, where each infrastructure network is graphically and operationally assessed, according to the municipal administrations' different road interventions in each period after the construction of the modeling networks. Likewise, the graphic components (connectivity, directionality, lengths of the arcs and nodes) are verified using ArcMap's Topology and TransCad's Check Line Layer Connectivity extensions.

Phase 3 – Geographical accessibility: Once the road-infrastructure network assessment has been carried out, the travel times by public transport for each infrastructure network are determined. The procedure considers equation (1) (Montoya et al., 2021) as a preliminary construction basis, in which the travel time of each section of the road network is determined.

Where $Tv_{link\ i}$ is the travel time of link i, obtained from the division between the length and speed of each link.

Once the travel times for each segment of the infrastructure networks have been obtained, the travel time matrix is constructed by applying Dijkstra's algorithm (Dijkstra, 1959), Dijkstra's algorithm is a well-known method for solving the single-source, shortest-path problem in a weighted graph. Its objective is to determine the shortest path from a starting location, x, to a destination location, j. The algorithm maintains a set of junctions, C, which represents the junctions whose final shortest path from s has already been calculated. In each iteration, the algorithm selects a junction from the set of junctions that has the minimum estimated shortest path, adds it to the set C, and updates the shortest-path estimates of its neighboring junctions that are not yet in S. This process continues until the destination junction is added to C. Next, the vector of average travel times for each network node associated with the time matrix is structured using equation (2) (Montoya et al., 2021).

$$Tv_{link\ i} = \frac{l_{link\ i}}{s_{link\ i}} \tag{1}$$

$$\overline{Tv}_{nodo\ x} = \frac{\sum_{j=1}^{n} tv_{x,j}}{n} \qquad x \text{ € } \{nodo_1, nodo_2, \ldots, nodo_n\}; j\text{€}\{nodo_1, nodo_2, \ldots, nodo_n\}; \tag{2}$$

Where Tv_{xj} is the shortest of the travel times from node i to municipality j, within the set of values obtained from Dijkstra's algorithm, n is the total number of nodes in the network, and finally $\overline{Tv}_{nodo\ x}$ is the average travel time to node i, product of the division of the times to each node of the network by the number of existing nodes.

After obtaining the vector of average times, the data interpolation process is developed to characterize the travel cost of each scenario implemented, using the geostatistical method of Ordinary Kriging, considering the spatial separation of each point and being able to establish the accessibility polygons visualized using time contour lines in each study network.

Phase 4 – 2.4. Population coverage analysis: As a final methodological item, the analysis of population coverage is carried out, where the average travel time is evaluated for each stratified population group based on the use of infrastructure. This analysis aims to identify the population groups with greater ease of movement in public transportation, assuming that every citizen can use the service regardless of their purchasing power or additional modes of transportation they may have.

For the construction process, the intersection of the geographic accessibility curves and the population and area polygons of each study area is carried out using ArcMap's Geoprocessing Intersect tool, in which the information of each layer is superimposed, enabling significant information to be assigned to each sector of the study area. Once the intersection has been carried out, the population groups included in each time polygon are characterized or identified. Then, using Microsoft Excel, the percentage of coverage of each transport system analyzed is constructed.

RESULTS AND DISCUSSION

As a result of the evaluation of geographical accessibility by public transport in the study cities, Figures 2, 3, and 4 show the average travel time at 2-minute intervals. The same color scale is used to consistently assess the travel times in the different cities, including the maximum and minimum values of the transport networks evaluated.

Figure 2 shows the travel costs obtained for Manizales, ranging from 18 to 74 minutes. This assessment shows that the sectors with the highest travel costs are the areas of La Linda and Maltería, located in the city's peripheral corridor. The lowest travel costs are observed in the CBD sector (Central Business District), with an average minimum travel time of 18 minutes. This behavior is directly associated with the availability of routes in the sector, which allows users to travel more easily.

Continuing with assessing accessibility in the study cities, Figure 3 shows the average travel cost for Armenia. The minimum travel time identified is 20 minutes on the Brasilia Nuevo - CBD corridor. Regarding the behavior observed in Manizales, it can be seen that Armenia requires an additional 2 minutes on average as a base point of coverage.

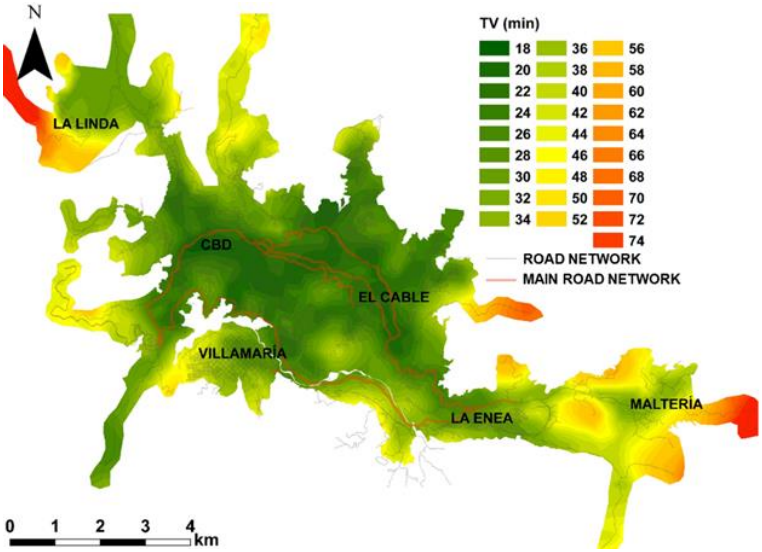

Figure 2. Geographical accessibility curves for the city of Manizales (Source: Authors)

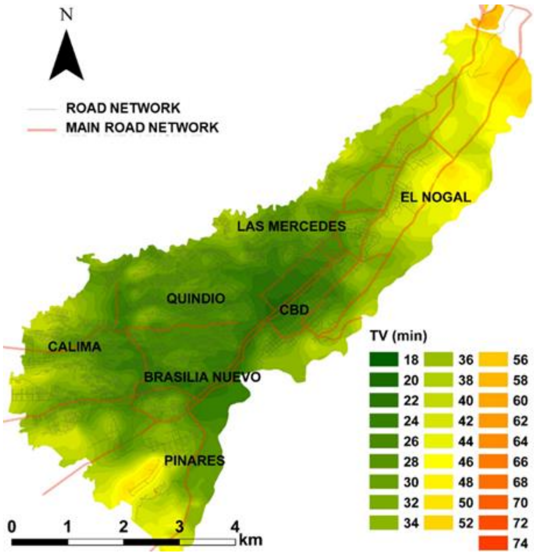

Figure 3. Geographical accessibility curves for the city of Armenia (Source: Authors)

However, the final valuation differs by around 22 minutes, showing a maximum of 58 minutes. This variation implies that the layout of the transport routes in Armenia has a better distribution concerning the peripheral areas. Next, the accessibility assessment for the Pereira-Dosquebradas integration shows an interesting accessibility behavior concerning the previous assessments. This assessment is based on the area's transport structure, which operates on BRT (Bus Rapid Transit) services that facilitate travel around the peripheral sectors. Its minimum value in terms of travel time is over 20 minutes to the CBD sector; however, the maximum time identified is over 46 minutes, which is the lowest time in the area under analysis.

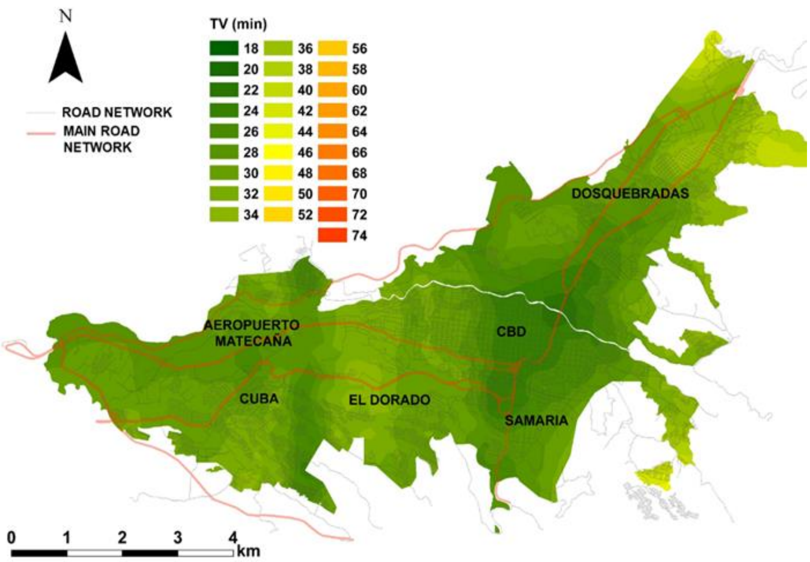

Figure 4. Accessibility curves for the Pereira-Dosquebradas integration (Source: Authors)

Figure 5 shows the behavior of population-based cumulative coverage in each city under study, considering the distribution within each analyzed city. It is important to clarify that, despite observing higher times in the accessibility curves corresponding to urban areas, the population distribution is more concentrated towards the city center. As a result, the population can be covered in a shorter average time than the maximum recorded in the urban environment.

It is identified that the best coverage offered is in Manizales, which requires an average travel time of 25 minutes to cover more than 60% of its population, while the curves associated with Armenia and Pereira show similar behaviour up to 30 minutes, in which they manage to cover 60% of their populations. However, after this time, Armenia requires the longest travel time to cover 100% of its inhabitants.

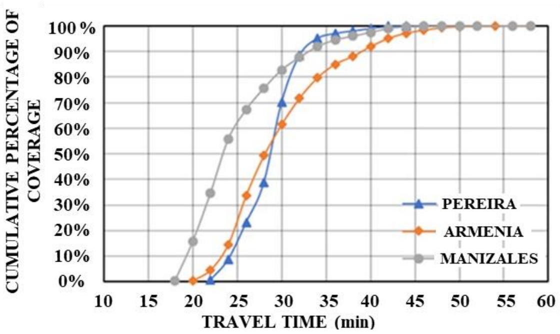

Figure 5. Comparison of population coverage for the study cities (Source: Authors)

Figure 6 shows the assessment of population coverage, disaggregated by socio-economic stratification, where it can be seen that, for stratum 1, the service's availability operates similarly in each city, with a time of 30 minutes to supply 60% of the population. In strata 2 and 3, similar behavior is observed, with a more significant opportunity for coverage in Manizales, with around 24 minutes to supply 60% of the users, while in Armenia and Pereira, at least 30 minutes are required to achieve the same coverage. The behavior associated with stratum 4 shows a significant separation in coverage for the cities of analysis, with times of between 24 and 28 minutes to achieve more than 60% of the population, with a vital crossing of the curve of Pereira, which, in a time of 32 minutes, satisfies the requirements of the inhabitants of this stratum.

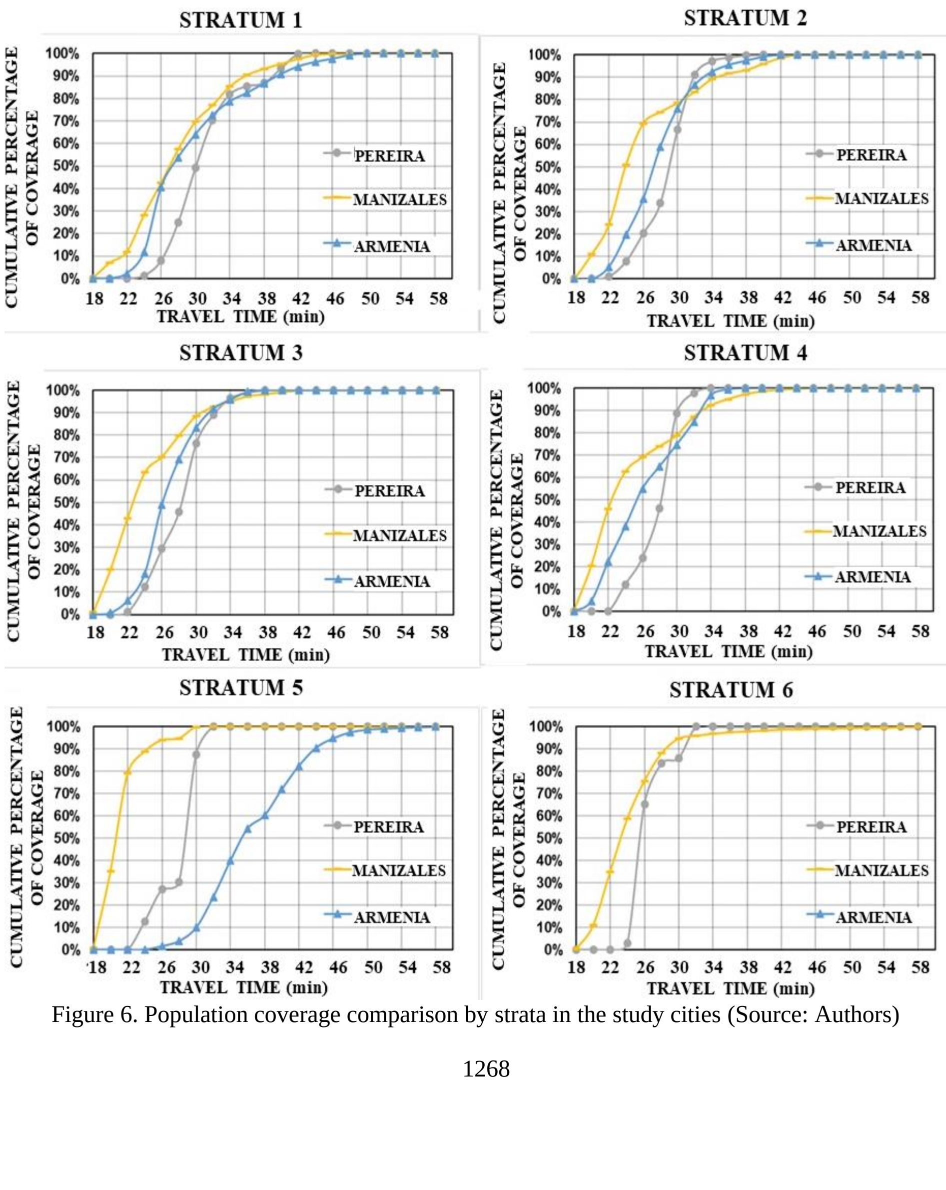

Figure 6. Population coverage comparison by strata in the study cities (Source: Authors)

The assessment observed for stratum 5 shows the most significant separation between curves, giving the best coverage to Manizales users with a travel time of 20 minutes. It manages to cover more than 60% of users, then Pereira with a high slope over 30 minutes, and finally Armenia with a requirement of up to 38 minutes to meet at least 60% of its population.

Finally, the socio-economical stratum 6 has the best coverage in Manizales, with a travel time of fewer than 24 minutes for 60% of users, a time similar to the environment observed in Pereira but with a greater slope. Concerning users in Armenia, it is not possible to assess due to the low concentration of users in this stratum and the impossibility of locating them. Moving on from the population assessment, Figure 7 shows the variation in coverage concerning the variable area of the urban environment in each study city, which are 42.89 km2 for the Pereira-Dosquebradas area, 31.57 km2 for Armenia and 58.09 km2 for Manizales. In the first instance, the behavior between curves is similar, with a slight predominance in Manizales requiring less travel time as a starting point. However, after 26 minutes, the urban environment area of Pereira manages to be covered faster than that shown between Manizales and Armenia, which require up to 56 minutes and 74 minutes, respectively.

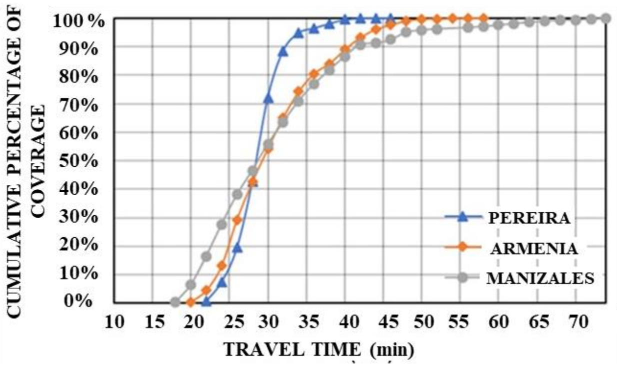

Figure 7. Comparison of area coverage for the study cities (Source: Authors)

CONCLUSION

According to the variation in the accessibility and area curves, it can be seen that the best coverage concerning the travel time observed is in the Pereira-Dosquebradas area, bearing in mind that the maximum values identified are substantially lower than those observed in Manizales and Armenia.

However, the population valuations presented show that the provision of transport services in Manizales manages to meet the needs of the inhabitants in less time than in the comparison cities. This behavior can be associated with the city's population distribution, where the residential tendency is towards the central sector and decreases concerning the peripheral areas, as opposed to the comparison cities, where the population is more evenly distributed with respect to the urban environment of the city. In this sense, Manizales has the best public transport coverage.

However, in a possible process of urban expansion, it could fall short in terms of coverage, which is different from the Pereira-Dosquebradas area due to the transport support offered by the BRT system. From the evaluations carried out, it can be concluded that the accessibility evaluation allows a more efficient observation of the public transport offered in an urban environment and the possibility of comparing the functionalities of different areas of analysis.

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