Geojournal of Tourism and Geosites
ISSN 2065-0817, E-ISSN 2065-1198

Year XVII, vol. 53, no. 2, 2024, p.462-469
DOI 10.30892/gtg.53209-1221

SPATIAL COVERAGE ANALYSIS OF BUS STOP SET AND ITS RELATIONSHIP TO THE SURROUNDING LAND USES. CASE STUDY, MANIZALES, COLOMBIA

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Citation: Montoya, J.A., Escobar, D.A., & Moncada, C.A. (2024). SPATIAL COVERAGE ANALYSIS OF BUS STOP SET AND ITS RELATIONSHIP TO THE SURROUNDING LAND USES. CASE STUDY, MANIZALES, COLOMBIA. *Geojournal of Tourism and Geosites*, 53(2), 462–469. https://doi.org/10.30892/gtg.53209-1221

Abstract: The main objective of the research is to determine the efficiency in population and area coverage of the set of bus stops to existing land uses in the city, allowing the identification of possible shortcomings, which leads to the formulation of restructuring proposals in terms of the location of the stops. The research methodology to be applied includes the use of geo-statistical models of accessibility based on GIS-type digital tools, supported by the collection of field information and road inventories. As a main result, it is obtained that the stop-system coverage allows the access of more than 80% of the population in a trip time by walking less than 5 minutes. Likewise, it is possible to identify a robust redundancy concerning the system of stops. Thus, it is concluded that the research process facilitates the evaluation and identification of possible interventions, guaranteeing a better coverage of the stops set regarding the city's existing activities.

Keywords: land uses, public transportation, bus stops, planning, accessibility

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INTRODUCTION

This research is part of the doctoral process of engineer Jorge Alberto Montoya Gómez, under the research Methodological Proposal for Variable Coverage Calculation from Public Transport Stops, Through the Application of Geographical Accessibility Models. Public transportation plays a fundamental role in shaping land use in urban areas, significantly influencing accessibility and the spatial distribution of activities. The availability and efficiency of public transportation directly impact the mobility of urban residents and workers, determining where they choose to live, work, and recreate (Jhonson, 2023). Recent research, such as that conducted by García at 2023, highlights that a well-planned public transportation system can promote urban densification and diversification of land uses by facilitating access to various areas of the city (García et al., 2023). This approach helps reduce dependence on private transportation, promoting a more sustainable and equitable development in urban environments.

In conclusion, public transportation not only enhances the connectivity and mobility of citizens but also influences the structure and function of land uses, contributing to comprehensive urban development. On the other hand, growth and development of an urban center are directly linked to the provision of an adequate and operative transportation system, given the population's travel needs concerning the location of employment, services, and other activities required in their daily lives (Murray et al., 1998; Urbano et al., 2012). However, on multiple opportunities, urban planning focuses on the implementation of measures to facilitate individual transportation, thus providing more infrastructure and services for private vehicles, leaving aside the functionality of public transportation systems, resulting in greater problems of congestion, environmental impact, public health, among others (Jakob et al., 2006; Nurdden et al., 2007).

These impacts caused by private transport have led to a new wave of review and projection of public transport systems as a structuring axis of development, a contribution to the mitigation of environmental impacts (Miller et al., 2016), and improvements in the population's quality of life (Saif et al., 2019). As a result, transport system evaluation methodologies (Seker and Aydin, 2020), with emphasis on user accessibility (Saif et al., 2019), access to the system (Murray et al., 1998; Kaszczyszyn and Sypion-Dutkowska, 2019), safety (Araya et al., 2022), land use (Geurs and van Wee, 2004), and others.

However, these evaluation methodologies, although they allow estimating or visualizing the operational condition and the resulting benefits, do not allow a cross-cutting assessment of the various fields that may influence the behavior of users

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and/or the system, resulting in insufficient or conflicting intervention proposals regarding issues parallel to transportation. A clear example of this is the structuring of bus stops, where their location is based on general demand points and operational coverage radii, which are between 250 and 400 meters (Ibeas et al., 2010; Furth and Rahbee, 2000), seeking a balance between walking distance for users and the shortest stopping time for the displacement of vehicles (Giannopoulos, 1990). However, this methodology rarely considers important aspects such as the safety of the area where the stop is proposed, the surrounding slope, the vehicular flow and, most importantly, the land use on which it will operate. And it is that the conception of land use as a primary element of the "new urbanism", developed for decades (Newman and Kenworthy, 1996), has a direct relationship with transport systems, considering that the current conception is the urban development oriented to transport (Segura and Jiménez, 2019), in which the development poles (activities - land uses) and the existing infrastructure for the interaction of these activities are determined, ensuring more efficient use of land allowing the functions that generate more trips to be concentrated in the proximity of public transport and thus minimizing dependence on private vehicles (Vecchio, 2021). In this vein, assessing the relationship between land use and bus stop coverage ensures a better perception of the best location of bus stops and improves access conditions for users.

As a prelude to the development of the methodology, it is necessary to understand and differentiate the terminology of accessibility, which has been known since the twentieth century second decade (Batty, 2009) but recognized mainly by definition established by Hansen in 1959, "the potential of opportunities for interaction" (Hansen, 1959). However, although Hansen's definition is considered as the fundamental basis of accessibility, as an example of this we have the definition of Dalvi and Martin "ease with which some land use activity can be achieved" (Dalvi and Martin, 1976), the definition of Ben-Akiva and Lerman "the benefits provided by a transportation/land use system" (Ben-Akiva and Lerman, 1985) and the definition proposed by Burns in 1979 "the freedom of individuals to decide whether or not to participate in different activities" (Burns, 1979). Although each definition has significant support, within the research, we chose to define accessibility as a measure of the potential for interaction between human settlements based on the use of a mode of transportation and the limitations of its scope, given the existence of barriers (Geurs and van Wee, 2004; Morris et al., 1978). This to characterize how accessibility is "measured" since there are different ways of quantifying it according to the needs of each research. The location-based (Geurs and van Wee, 2004) is used as an accessibility measure for the analysis, considering the stops layout in the study area and the surrounding land use. It is also related to contour assessments due to the visualization structure in which the information is presented.

Considering the above, this research proposes to perform a cross-sectional analysis of access coverage to Public Transportation Systems, considering bus stop locations, existing population, and surrounding land use through the application of geographic accessibility models based on GIS software, complemented with sociodemographic analysis. All this is to determine the efficiency in population and area coverage of the set of bus stops to existing land uses in the city, allowing the identification of possible shortcomings and characterize if the current bus stop location guarantees the correct access to the transport system, in addition to indirectly assessing its efficiency. The proposed study area is the city of Manizales, the capital of the department of Caldas, Figure 1, located on the western flank of the central mountain range of the Colombian Andes. Manizales has a total population of 458,442 as of 2023, according to the report submitted by the National Administrative Department of Statistics - DANE (Dane, 2018), of which 434,006 correspond to the urban area. The city's topography has a strong variation due to its high mountain location, resulting in difficulties of expansion or particular adaptations for urban development. Regarding the functionality of its public transportation system, it has a total of 66 active transportation routes and 2 aerial cable lines, distributed in 8 companies, which operate independently in the modality of semi-automobile, taking responsibility for the service provided (Alcaldía de Manizales, 2017).

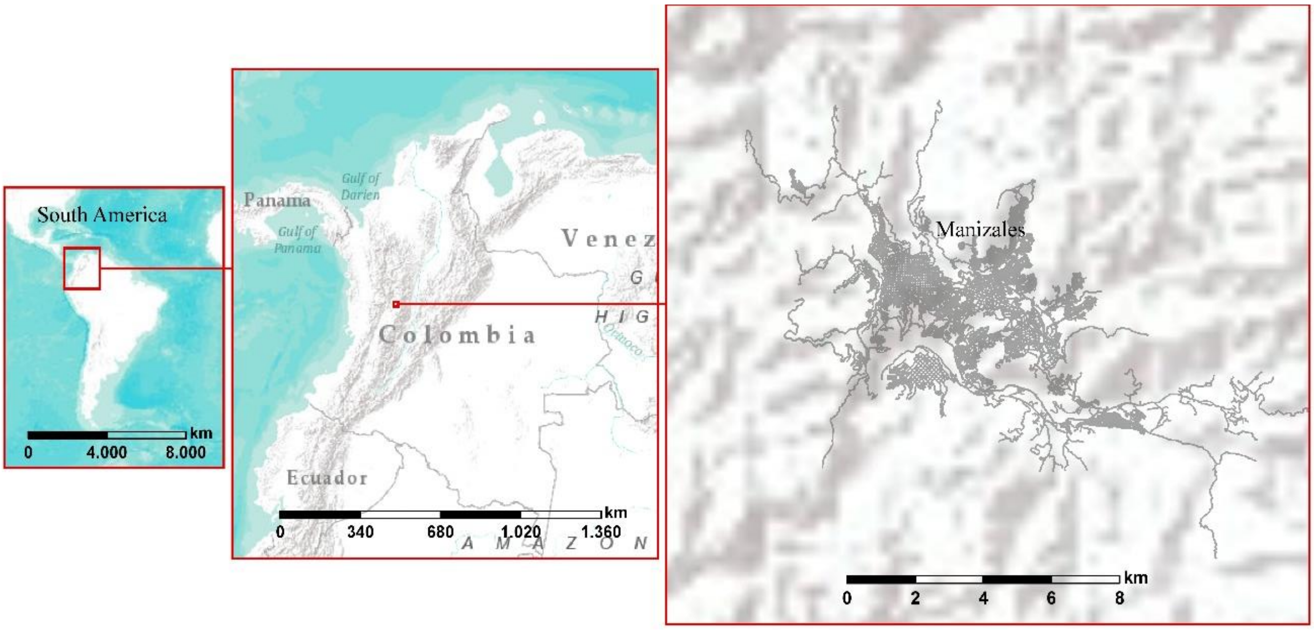

Figure 1. Study area location (Source: authors)

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.

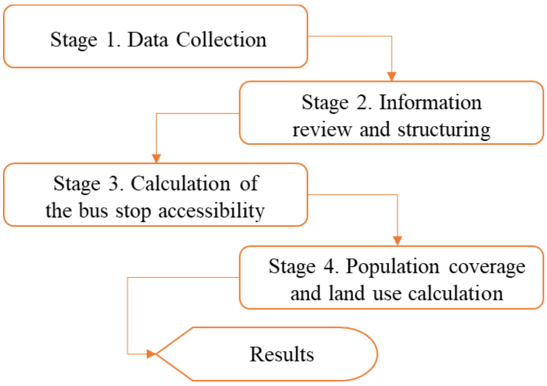

Figure 2. Research methodology (Source: authors)

Phase 1 – Data Collection: As a first methodological stage, we proceed to collect the necessary data for the analysis structuring, including the information base of the public transport system bus stops of Manizales - Villamaría, composed of a total of 1214 stops, as well as the pedestrian infrastructure network, on which the cost of displacement will be determined (Alcaldía de Manizales, 2017). At the same time, information on land use is obtained from the current Land Use Plan (Alcaldía de Manizales, 2017), composed of 5 categories -Institutional, Industrial, Residential, Mixed (commerce, residential, services), and Structuring Mixed (commerce, services, residential on the main axis of the city). In addition to the layer of population information and socioeconomic condition, which is characterized by socioeconomic strata, representative of the purchasing power of the population by groups from 1 to 6, where 1 represents the most unfavorable condition and 6 the population with the greatest economic capacity (Dane, 2023). It is important to clarify that, due to the proximity of Manizales to Villamaría, the operation of the transport system operates for both municipalities. However, the objective of the research is focused solely and exclusively on the urban area of Manizales since the information obtained on land use, and the population does not include data related to the municipality of Villamaría. Figure 3 shows the base information collected.

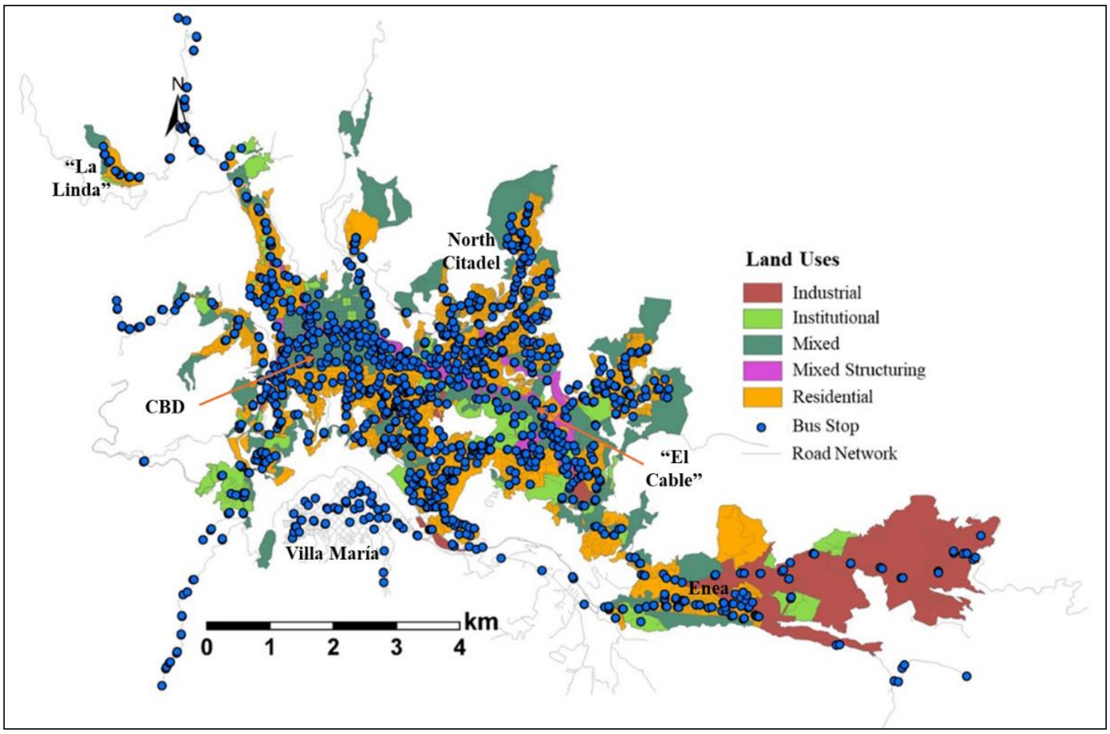

Figure 3. Baseline data collected (Source: authors)

Phase 2 – Information review and structuring: Once the basic information has been compiled, the data needed for the analysis is reviewed and structured. The connectivity condition and components of the pedestrian infrastructure network are reviewed, corroborating the speed, directionality, and lengths of each associated section. The process is performed using the Topology extension of ArcMap, valuing each of the rules required for the execution, as shown in Figure 4. Regarding the bus stops, their location is verified by field verification, modifying the location of some points that do not have the correct location. This verification is done by using GPS and ArcMap restructuring. In Figure 5, The photographic record carried out by the authors of some city bus stops can be observed, which show the basic features, including shelter, seating, and signage. On the other hand, the information coming from the Land Management Plan is kept in its original structure, except for the population information, which is updated according to the population projections defined by DANE.

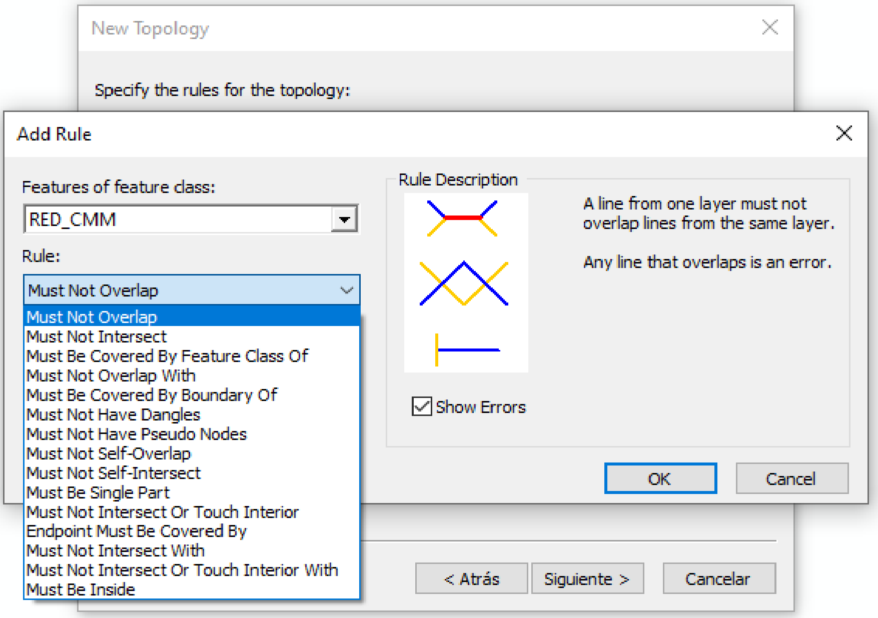

Figure 4. Topology (Source: authors)

Figure 5. Bus Stop revision (Source: authors)

Phase 3 – Calculation of the bus stop accessibility: The following methodological step is determining users' travel costs to the nearest stop. This procedure includes the travel time calculation for each network segment using Eq. 1 (Montoya et al., 2021), which is required to determine the minimum path from each network node. The shortest path definition is based on Dijkstra's algorithm (Dijkstra, 1959), where the evaluation of the existing path from each network node to each of the available stops is performed by iteration (Eq. 2) (Montoya et al., 2021), to select the one with the lowest cost of the multiple available ones. The operational process of analysis is performed using the new closets facility extension of ArcMap, linking the bus stops as Facility and the network nodes as Incidents.

$$Tv_i = \frac{x_i}{S_i} \times 60 \tag{1}$$

Where Tv_i is the travel time of arc i, X_i is the length of arc i and S_i is the arc velocity.

$$\begin{gathered} Tvmin_i = min(Tv_{ij}) \\ j = 1{:}n,\quad Tv_{ij} = min\{Tv_{ij_1}, Tv_{ij_2}, \dots, Tv_{ij_m}\}, m = Roads \end{gathered} \tag{2}$$

Where $Tvmin_i$ is the minimum travel time to the nearest stop j, from node i of the multiple paths m available.

Once the displacement times of each node are obtained, the accessibility curves are constructed using the Geostatical Wizard extension of ArcMap, considering the ordinary Kriging as interpolation method (Eq. 3) (Montoya et al., 2021), and the incorporation of semivariogram for the correlation assessment of the existing data (Eq. 4) (Montoya et al., 2021),.

$$Z(So) = \sum_{i=1}^{N} \lambda i Z(Si) \tag{3}$$

Where $Z(S_i)$ is the measured value at location i, λ_i the weighting for the measured value at location i; So, the prediction location and N the number of measured values.

$$\gamma(h) = \frac{\sum (Z(x+h) - Z(x))^2}{2n} \tag{4}$$

Z(x) is the value of the variable at site *X*, *Z(x+h)* is the value of the variable separated from the previous site by a distance h and n is the number of pairs separated by this distance.

Phase 4 – Population coverage and land use calculation: After defining the displacement cost of each network node using the accessibility curves, the population, and land use information is cross-referenced by superimposing layers, allowing a time value to be assigned to each land use polygon and associated population. Subsequently, the information is processed using the Microsoft Excel tool, resulting in population coverage and land use.

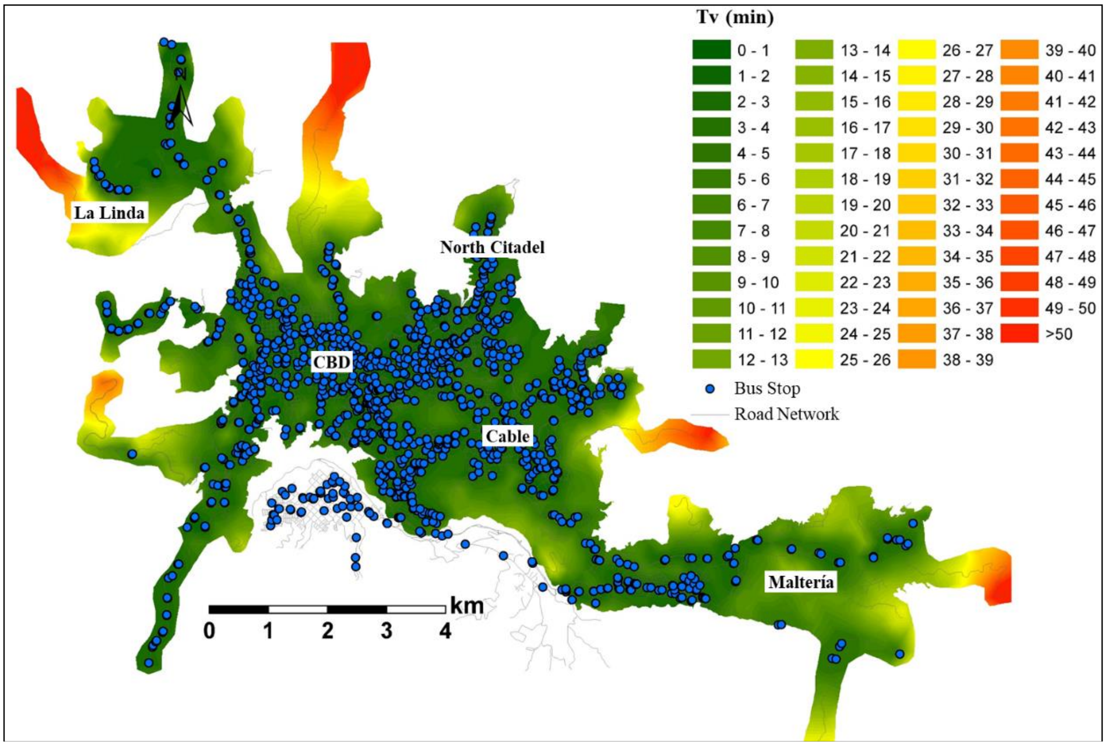

Figure 6. Accessibility curves (Source: authors)

RESULTS AND DISCUSSION

As a result of the assessment made of the set of bus stops, Figure 6 shows the behavior of accessibility at 1-minute intervals for the area of Manizales. It is possible to observe that most of the city's urban area can be accessed in a travel time of fewer than 13 minutes, thus allowing users of the transport system to use the system in a relatively low base time. However, there are some areas of the city with requirements of up to 50 minutes or more. On the other hand, there is a high concentration of bus stops towards the inner part of the city, inferring a higher demand for users.

However, this high number of bus stops could significantly impact the system's operation. Regarding land use defined by the municipal administration vs. travel time, Figure 7, there is a general coverage of up to 37 minutes to get from any of the areas to the nearest stop.The following Figure 8 and Figure 9 show the percentage of coverage achieved by population and type of land. Figure 8 shows that the population can access at least one bus stop in a travel time of fewer than 5 minutes for an accumulated percentage of more than 80% for each stratum, with strata 1 and 6 being those with the least accessibility, despite having a positive evaluation. This behavior allows relating the location of the stops to the city's population, in which if a standard walking speed of 4.32 km/h is considered, it is possible to affirm that any user would have a bus stop in a radius of fewer than 360 meters, being within the recommended interval defined by other authors (Ibeas et al., 2010; Furth and Rahbee, 2000). However, the coverage value is 50% of the population.

In that case, there is a time requirement of at least 2.4 minutes, translating into an average distance to a stop of 172 meters, a value lower than the recommended in theory. This behavior affirms that, in a large part of the city, there is an oversupply of bus stops, which could affect the system's operability.

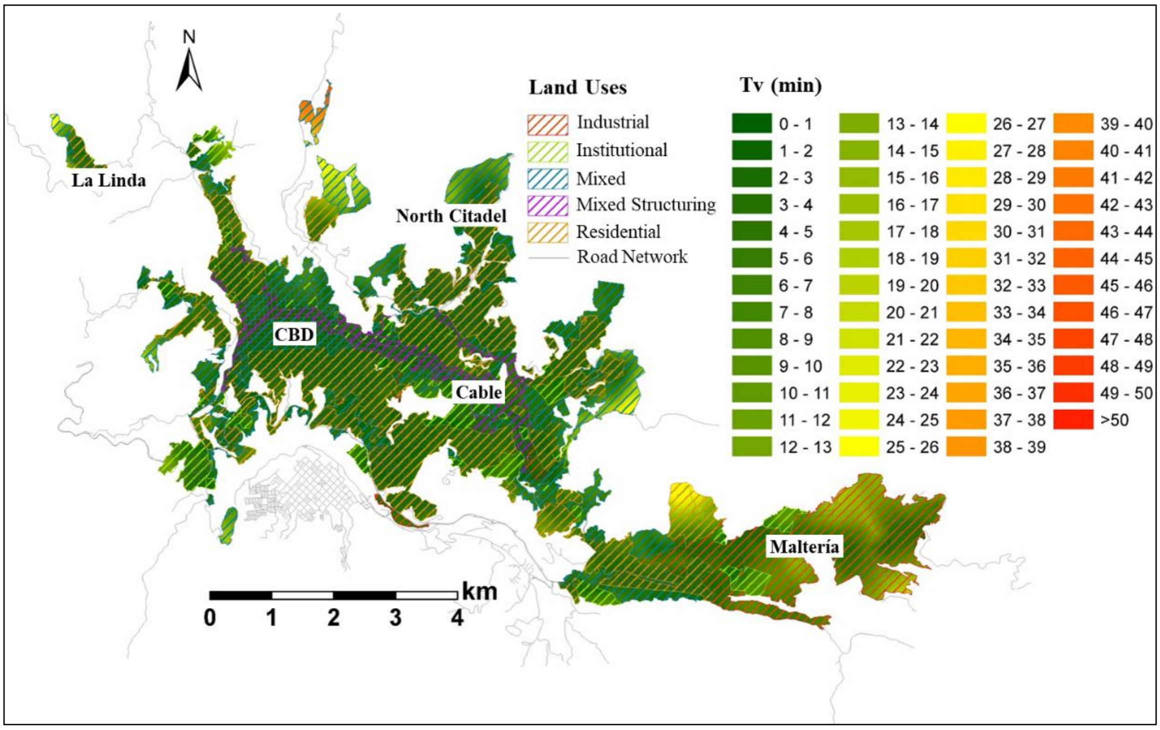

Figure 7. Accessibility curves vs. land uses (Source: authors)

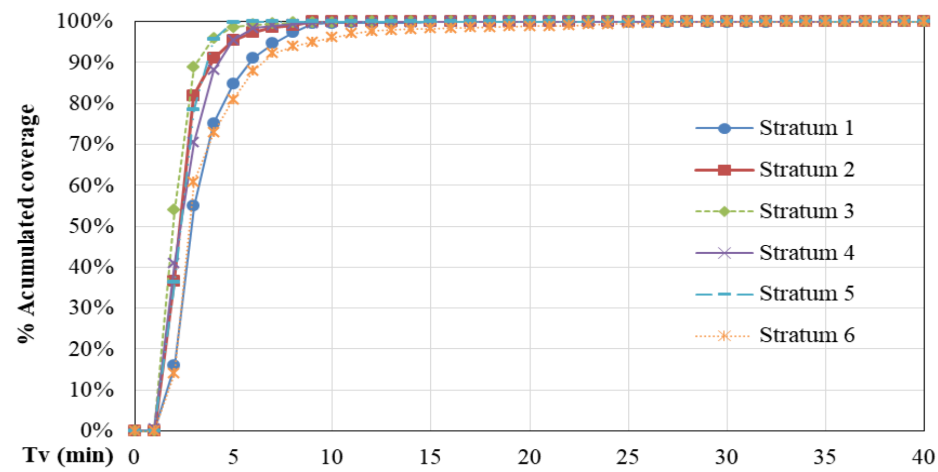

Figure 8. Cumulative percentage of population coverage by socioeconomic stratum to all bus stops (Source: authors)

Regarding Figure 9, the evaluation of coverage by land use is shown for the set of bus stops. The location of the bus stops obeys the distribution of the population in the residential and mixed land uses, which host more than 87% of the population. However, a more critical requirement in access time is observed for the institutional, industrial, and mixed land uses, which host labor, educational, commercial, and service activities, allowing us to infer that the current layout favors the types of trips with origin at home and not the conditions of origin in the daily activities. This evidenced behavior leads to great alerts regarding how the stops are located since by not allowing an adequate distribution (balanced), people require a longer walking distance to access places of interest, even more so at the end of long and tiring days, causing increases in access times and loss of interest in the use of the service, which results in a higher probability of migration to other modes of transportation such as motorcycles. As a general assessment, it is possible to state that the current bus stop layout in the study area facilitates access to the system users from their homes. However, the current layout lacks a balance that facilitates displacement from the points of daily activity, reaching times of up to 10 minutes, which exceed the 400-meter radius recommended for the location of the bus stops.

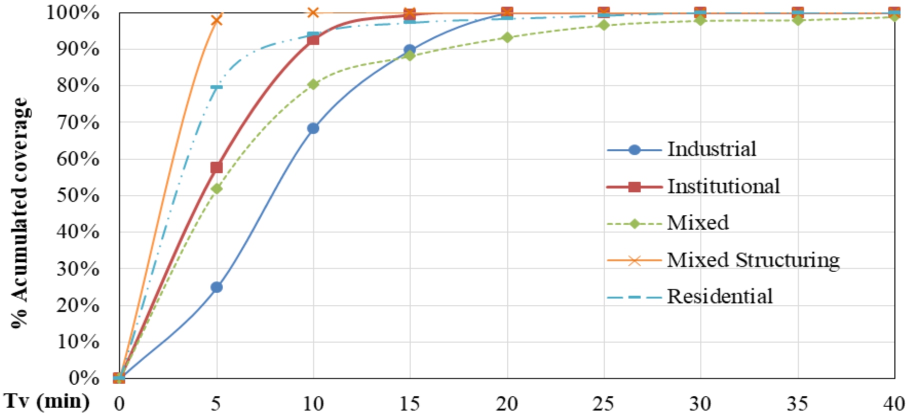

Figure 9. Cumulative percentage of coverage by land use (Source: authors)

On the other hand, although there is no valuation of accessibility within the transportation system, it can be stated that, given the conditions of redundancy and oversupply of stops, high delays can be caused in the operation of the service, considering the detention times, passenger boarding and alighting, as well as the energy cost when accelerating and decelerating the transport units, which could result in a higher operating cost that would eventually deteriorate the system. In this sense, a redistribution of the current location of the stops should be chosen, in search of a more outstanding operational balance, with a fair value according to the existing methodologies and considering the different land uses of the city.

CONCLUSION

The main conclusion of the study is that, although the current design of bus stops ensures adequate access to the transportation system by providing low travel times to users, there is an excess in the distance required for 50% of the population, which could be detrimental to the system in terms of efficiency and convenience. Furthermore, it is observed that the current design of bus stops predominantly favors residential areas of the city, leaving some gaps in work areas. This could result in a migration between transportation modes and affect accessibility and mobility in these areas. The joint assessment of population coverage, stratification, and land use provides a more comprehensive view of the operational condition of the transportation system, facilitating the identification of areas for improvement and the implementation of strategies to optimize service provision without sacrificing its operational effectiveness.

Accessibility plays a crucial role in the evaluation of bus stops and their relationship with land use. This interconnection is essential for understanding how the characteristics of the urban environment influence the efficiency and effectiveness of the public transportation system. The strategic location of bus stops, based on the distribution of population and economic activities, directly affects the accessibility and convenience of the service for users. Furthermore, assessing accessibility can reveal disparities in public transportation coverage, which can influence mobility and residents' quality of life. Therefore, considering accessibility in the planning and design of bus stops is essential to ensure equitable and efficient access to public transportation, which in turn can contribute to the promotion of sustainable urban development and greater social inclusion.

Author Contributions: Conceptualization, J.A.M. and D.A.E.; methodology, J.A.M., D.A.E. and C.A.M.; software, J.A.M. and C.A.M.; validation, D.A.E. and C.A.M.; formal analysis, J.A.M. and C.A.M.; investigation, D.A.E. and J.A.M.; data curation, J.A.M.; writing - original draft preparation, J.A.M.; writing - review and editing, D.A.E. and C.A.M.; visualization, J.A.M. and D.A.E.; supervision, C.A.M.; project administration, D.A.E. All authors have read and agreed to the published version of the manuscript.

Funding: Not applicable.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study may be obtained on request from the corresponding author.

Acknowledgments: The authors would like to thank the Sustainable Mobility Research Group and the Universidad Nacional de Colombia Vice President's Research Office - Manizales for their contribution and support in the research development of project 47163, "Methodological proposal for the definition of public transportation planning instruments through geospatial coverage analysis, sustainability, and citizen education," within the framework of the "Convocatoria Nacional Para El Fomento de Alianzas Interdisciplinarias Que Articulen Investigación, Creación, Extensión Y Formación en la Universidad Nacional de Colombia 2019-2021".

Conflicts of Interest: The authors declare no conflict of interest.

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Article history: Received: 28.01.2024 Revised: 28.03.2024 Accepted: 15.04.2024 Available online: 15.05.2024