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

Year XVII, vol. 53, no. 2, 2024, p.564-574
DOI 10.30892/gtg.53220-1232

PLANNING THE INSERTION OF SUSTAINABLE TRANSPORT MODES BASED ON AN ACCESSIBILITY ANALYSIS. CASE STUDY: SAN JOSÉ DEL GUAVIARE, COLOMBIA

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Citation: Romero, J.J., Escobar, D.A., & Moncada, C.A. (2024). PLANNING THE INSERTION OF SUSTAINABLE TRANSPORT MODES BASED ON AN ACCESSIBILITY ANALYSIS. CASE STUDY: SAN JOSÉ DEL GUAVIARE, COLOMBIA. *Geojournal of Tourism and Geosites*, 53(2), 564–574. https://doi.org/10.30892/gtg.53220-1232

Abstract: This research objective is to determine the impact on the operability of private vehicle transport mode, given the proposed implementation of the new bicycle route, pedestrian a transit network in San Jose del Guaviare (Colombia), with the aim to propose an urban planning instrument for decision-making that promotes the insertion of alternative transport means to a private vehicle. The methodology includes the application of transport infrastructure supply models as an evaluation basis, supported by geographical accessibility, coverage and geospatial impact analyses. The main results show that the proposal for the insertion of alternative modes of transport would be beneficial in terms of providing other mobility options for the inhabitants without deteriorating the current mobility conditions of the private mode. The above result point to the benefits that are shown for the municipality's development and planning to maximize their use by decision-makers.

Keywords: accessibility, transport modes, pedestrians, cycle routes, public transport, sustainability

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INTRODUCTION

Urban and land-use planning has been directly linked to the development of transport systems and the public policies of those who govern them. In recent decades, urban planning models have been developed that seek to represent in a simplified way the operational conditions of different modes of transport to make decisions in the short, medium, and long term (Ortúzar and Willumsen, 2008), in such a way that environmental sustainability concepts are involved in modal complementarity. These models take on great relevance as they justify large financial investments, which is a fundamental resource for cities in the context of developing countries such as Colombia; likewise, depending on the prioritized mode of transport, the environmental sustainability conditions of cities would be strengthened and improved through the implementation of adequate planning processes.

Accessibility is a term that has been used since the 1920s based on studies on location theory and regional economic planning (Batty, 2009). From the transport-supply-model point of view, it is defined as the potential for interaction opportunities that an individual possesses (Hansen, 1959). In this case, opportunities are defined as the different facilities in which some kind of relationship can be built, including jobs, education, hospitals, and commercial centers, among others. Dalvi and Martin (1976) defined the concept as the ease with which it is possible to reach a land use from a location using a particular transport system. Ingram (1971) classified accessibility into two types: i) relative accessibility, which is measured between two points; ii) comprehensive accessibility is measured from several points to one or vice versa. Later, Talen and Anselin (1998) defined another type of accessibility measure, which is made between all the road networks, each one taken as opportunities, which they call global average accessibility. Accessibility has been used throughout the world in issues related to transport project prioritization analysis (Escobar and García, 2012), sustainable development (Vega, 2011), health (Yiannakoulias et al., 2013), education (Walsh et al., 2017) and cycle path (Ferster et al., 2021), among others. Furthermore, in Colombia these analyses have been used since the beginning of the 21st century in issues related to transport infrastructure at the regional level. Besides, at the urban level in cities such as Bogotá D.C. (Guzmán et al., 2017), Manizales (Escobar and García, 2012), Pitalito (Montoya et al., 2018), among others.

San José del Guaviare, the Departmental capital city of Guaviare (figure 1), is home to 36,290 inhabitants in its municipal capital (DANE, 2018), is located in south-central Colombia (Figure 1) at 175 masl and a distance of 396 km from the national capital, Bogotá D.C.; its economy is based on trade, fishing, agriculture, and livestock (Gobernación del Guaviare, 2017). In

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terms of urban mobility, its inhabitants make journeys using a scarce pedestrian network, a deficient network of cycle routes, and motor vehicles; it should be noted that the municipality does not have a collective public transport system.

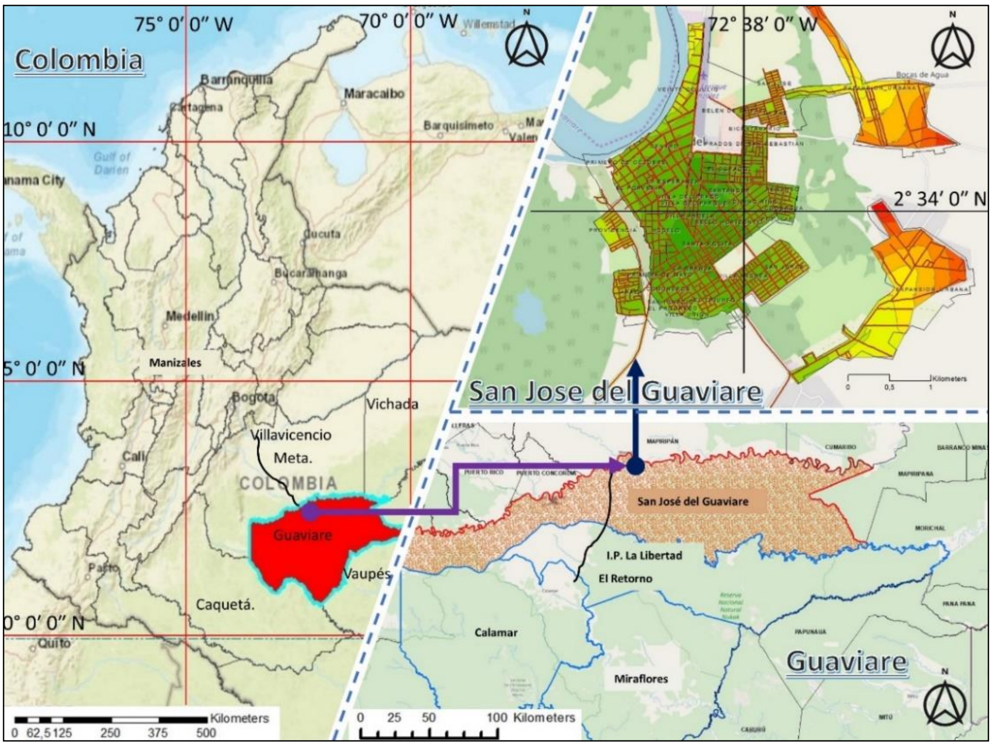

Figure 1. Municipality of San José del Guaviare (Source: authors)

On the other hand, the World Economic Forum (WEF) has made a series of priority recommendations, including those related to infrastructure, equipment, and environmental sustainability (CPC, 2020). This is to improve efficiency in the intervention of natural resources and conserve the natural capital that communities currently possess since in the last two decades the loss of natural resources and deforestation of large areas has been notorious in our country. In the WEF rating, San José del Guaviare ranked 28th out of 32 departmental capitals; however, in the environmental sustainability component, it ranked 2nd; however, in the infrastructure component, it ranked 27th, and in the mobility component, analyzed concerning passengers using public transport, it ranked last. This is the first time that a supply model has been applied in the municipality that develops a methodology for the best choice of infrastructure projects, thus creating a tool that will allow the identification of the areas that will get the greatest benefits in alternative modes of transport.

However, some analyses and implementations of this kind have been conducted in other parts of the world such as Polonia or Irán (Tahmasbi and Haghshenas, 2019; Radzimski, 2023), validating the importance of implementing sustainable transport modes, as well as assessments in urban environments (Sun et al., 2018) or considering traffic congestion and uncertain conditions (Babaei et al., 2023). The above will strengthen the formulation and implementation of development plans in the coming years in terms of environmental sustainability by promoting the use of environmentally friendly modes of transport. Taking the above into account, the objective is proposed, to determine the impact on the operability of private vehicle transport mode, given the proposed implementation of the new bicycle route, pedestrian a transit network in San Jose del Guaviare (Colombia), with the aim to propose an urban planning instrument for decision-making that promotes the insertion of alternative transport means to a private vehicle.

After this brief introduction, the methodology used in the research is explained, followed by a presentation and discussion of the results, and finally, the main conclusions are analyzed.

MATERIALS AND METHODS

The research methodology (Figure 2) consists of six sequential phases as described below.

Phase 1 – Transport Network Creation and Validation: At this first stage, shapefiles of urban polygons, environmental surroundings, and transport infrastructure networks are created using ArcMap software. For the calculation of the variable, it is essential to have the road network infrastructure; since if it does not exist, it is not possible to identify the modes of transport that provide accessibility to a specific site. The construction of the road network must follow certain suggestions; first of all, it must take into account the graph theory, which establishes that the road network must be built under arcs (roads) and nodes (road intersections); after this, the topology of the network is verified, which guarantees that the arcs and nodes are perfectly graphed and connected. As sources of information, official documents such as the Land Use Plan (Plan de Ordenamiento Territorial) and the Sectoral Environmental Management Plan (Plan de Ordenación Ambiental Sectorial) were consulted.

Phase 2 – Network Operational Analysis and Data Collection: Arc measurement (li) involves two key attributes: length and operational speeds (vi). Spatial length analysis utilizes GIS computational tools, and operational speed calculation considers the hierarchization of the transport infrastructure network (Zuluaga and Escobar, 2017). Field measurements with GPS devices and calibration using Google Maps, MapQuest, and Rand McNally databases have been conducted, updating values based on user-reported conditions (Wang and Xu, 2011; Lahoorpoor and Levinson, 2020). Calibration of the transport infrastructure network involves applying the minimum paths algorithm between two nodes (Dijkstra, 1959), comparing results with Google Maps and TransCAD to determine penalties (Cardona, 2018) for network balance in average travel time.

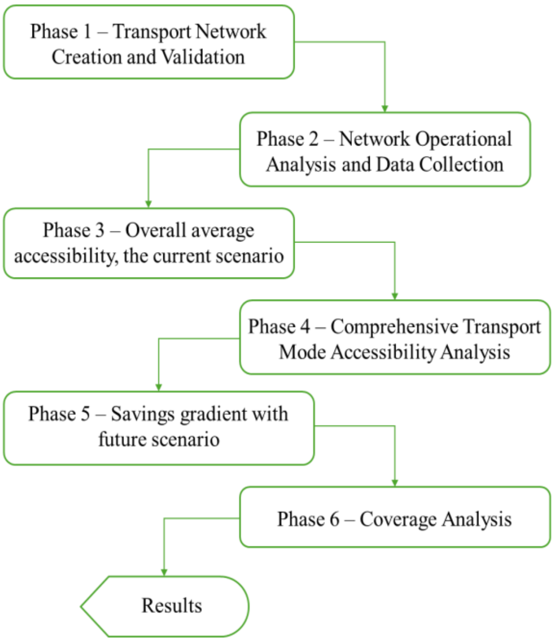

Figure 2. Methodology (Source: authors)

Phase 3 – Overall average accessibility, the current scenario: The overall average accessibility uses the existing transport infrastructure network to measure the connection conditions between all nodes of the road network by measuring the operational speeds along each of the 1533 arcs and 933 nodes of the network, which is an expression of the transport supply (Geurs and Van Wee, 2004). Likewise, the global average accessibility is considered a contour measure that relies on geostatistical analysis to make predictions throughout the territory. Initially, the travel time matrix (M_{tv}) is calculated through the Dijkstra algorithm, this matrix is of size n×n, where n is the total number of nodes in the network. Subsequently, the average travel time vector ($\overline{T_v}$) is calculated as shown in equation 1 (Perilla et al., 2018), where tv_{ij} is the average travel time between each pair of nodes (*i j*) expressed in minutes, and *n* is the total nodes used.

$$\overline{Tv_i} = \frac{\sum_{j=1}^{n} tv_{ij}}{n-1} \quad (1)$$

The Ordinary Kriging geostatistical model is used to build isochronous global mean accessibility curves, and one of the main points of its evaluation is the relationship between the data and its use for conjecturing, constructing, and modelling; as reflected in equation 2, considering that the semi-variogram is the central tool that decreases the mean square error of prediction, where *n* is the number of pairs of data separated by distance *h (meters)*, $Z_{(xi)}$ represents the value of the variable at position X_i and $Z_{(x+h)}$ is the value of the variable at distance $x+h$ X_i+h, *both in minutes.* (Matheron, 1962).

$$\overline{\gamma_{(h)}} = \frac{\sum \left(Z_{(x+h)} - Z_{(x)}\right)^2}{2n} \quad (2)$$

It states that the value of a variable can be predicted through the *n* random variables, as shown in equation 3, where λ_i. symbolises the weights of the original values (adimentional); these weights are calculated as a function of the distance between the sampled points $Z_{(xi)}$ and the point where the corresponding prediction is to be made $Z_{(x0)}$.

$$Z_{(x0)} = \lambda_1 Z_{(x1)} + \lambda_2 Z_{(x2)} + \lambda_3 Z_{(x3)} + \cdots + \lambda_n Z_{(xn)} = \sum_{i=1}^{n} \lambda_i Z_{(xi)} \quad (3)$$

In this case, the sum of the weights must be equal to one (1) for the predictor expectation to be equal to the variable expectation. The latter is known as the unbiasedness requirement (Giraldo, 2011). Finally, the curves are built from the prediction made; the curves are made for the current scenario and for each of the proposed intervention scenarios.

Phase 4 – Comprehensive Transport Mode Accessibility Analysis: This stage assesses overall territorial accessibility based on alternative transport modes. For pedestrian analysis, the existing infrastructure network is adjusted to a walking speed of 5.47 km/h (Transportation Research Board, 2016). For cycling, a speed of 20.8 km/h is considered (Transportation Research Board, 2016). The proposal for a real cycle route network is created, utilizing existing sections that allow cycling. For public transport, which currently lacks a network, proposed routes ensure connectivity between populated areas and primary activity nodes. The operational speed for accessibility calculations in this mode is set at 18.5 km/h.

Phase 5 – Savings gradient with future scenario: The savings gradient ($G.A$)is used to calculate the percentage change, in terms of average travel times, that would occur between the current scenario and the future scenario and thus establish the sectors of the study area with the greatest changes in their accessibility conditions. For its calculation, equation 4 (Cardona, et al., 2018b) is applied, where $\overline{Tvb}$ (minutes) represents the average travel time vector of the current scenario and $\overline{Tva}$ (minutes) represents the average travel time vector of the future scenario:

$$G.A\,(\%) = \frac{\overline{Tvb} - \overline{Tva}}{\overline{Tvb}} \times 100 \qquad (4)$$

Phase 6 – Coverage Analysis: In this step, the accessibility isochronous curves polygon and the neighborhood polygon data are intersected to create the percentage ogive of population coverage for each studied mode of transport. This intersection provides information on the percentage of the population covered by each mode of transport, along with the calculation of the average travel time weighted by the covered population. This facilitates a comparative and objective analysis of the proposed insertions.

RESULTS AND DISCUSSION

Initially, socio-demographic Shapefiles were created using the ArcMap software and the official urban map of San José del Guaviare (Gobernación del Guaviare, 2017). The transport network, comprising rigid pavement, flexible pavement, cobblestones, and paving, was meticulously established with 933 nodes and 1533 arcs, totaling 149.2 km. The walking mode of transport, currently nonexistent, was proposed to connect residential sectors with primary activity nodes.

Result 1 – Walking mode accessibility: San José del Guaviare lacks a promoted walking mode of transport. The proposed 130.3 km walking infrastructure aims to safely connect residential areas with primary activity nodes. The overall average accessibility reveals a predominant 20-minute isochronous curve in the Central Business District (CBD) (Figure 3), providing access to primary activity nodes. Districts with the best accessibility include Bello Horizonte, Bicentenario 2, El Divino Niño, El Dorado, La Esperanza, Popular, Santa Rosita, Santander, Villa Angela, Villa del Parque, and Villa del Prado. Meanwhile, the 20 de Julio and San José districts register longer travel times (32-33 minutes) despite being within the main urban polygon. Expansion areas show isochronous curves up to 60 minutes due to the significant distance from existing activity nodes. Figure 4 illustrates the cumulative population coverage for the walking mode, indicating that over 50% of the population can be covered within 20 minutes. The average weighted travel time is 23.8 minutes, emphasizing the population concentration in the CBD and underscoring the importance of strategically locating primary activity nodes in expansion areas to minimize motorized travel from the periphery to the CBD.

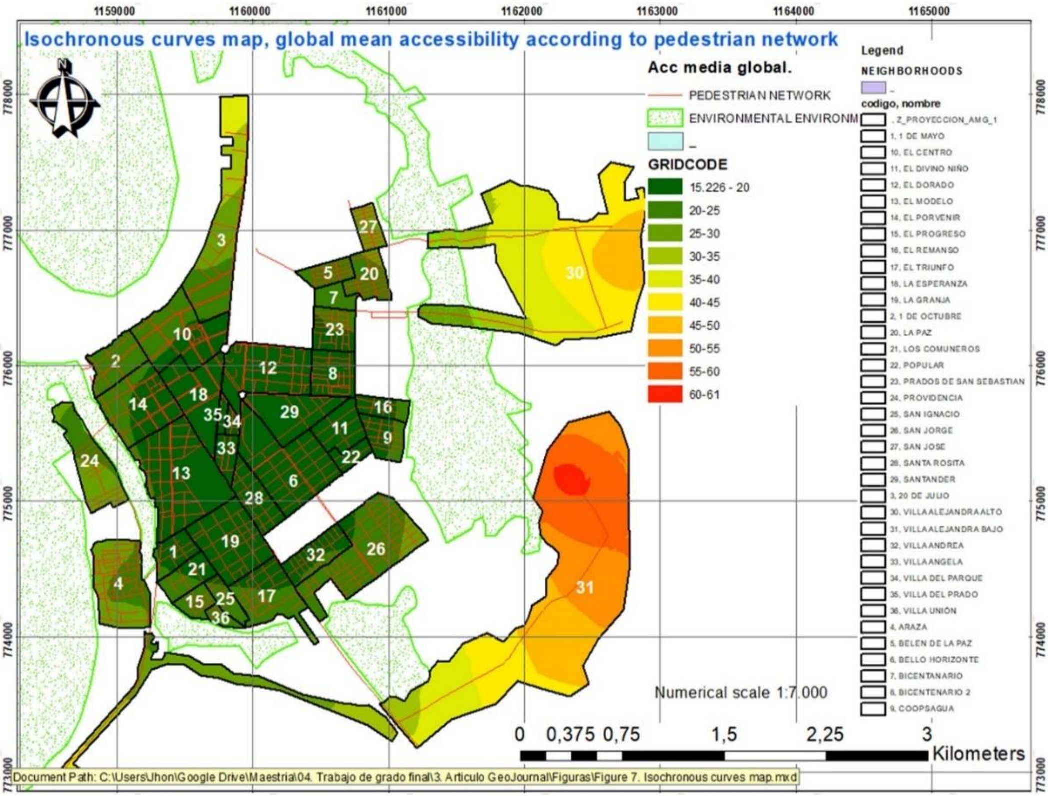

Figure 3. Overall average accessibility conditions. Mode of transport: walking (Source: authors)

Result 2 – Accessibility conditions for the cycling mode of transport: The bicycle-transport-infrastructure network is virtually non-existent, as only independent and disconnected arches were identified. The cycle route network (Figure 5) is proposed with the assumption of covering all nodes of primary activity (yellow) and seeking full coverage in the CBD of the municipality. The most remote neighborhoods of the network correspond to urban expansion areas such as San José, Arazá, Providencia, Villa Alejandra (high and low), located to the east of the municipality, where the conditions of the existing road infrastructure are deficient or are still paved without having defined a road profile.

The proposed walking mode of transport complements the cycle route network. The 7-10 minute isochronous curve covers 28% of the urban area and 46% of the total population, while the 20-minute curve covers over 50% of the walking population; in cycling, it covers 97%. This emphasizes the potential synergy between both modes, especially in connecting the eastern area to the municipality's CBD, where cycling takes up to 40 minutes. Figure 6 displays the cumulative population coverage percentage, highlighting significant coverage within a 15-minute average travel time. The population-weighted average travel time for cycling is 13.6 minutes, making it 1.75 times more efficient than walking.

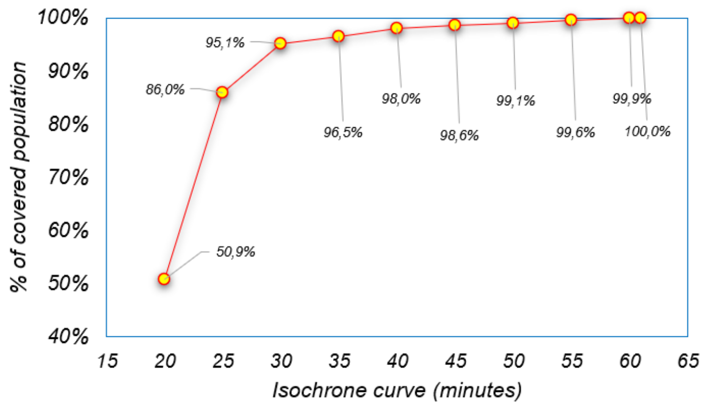

Figure 4. Ogive percentage of cumulative coverage. Mode of transport: walking (Source: authors)

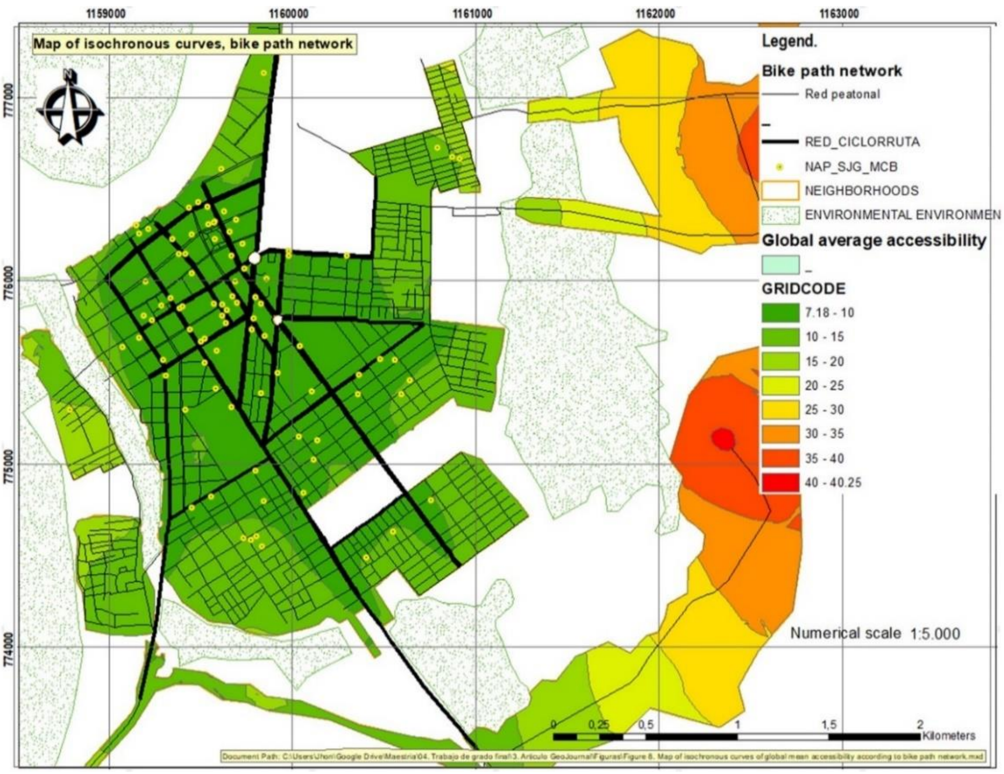

Figure 5. Overall average accessibility conditions. Mode of transport: bicycle (Source: authors)

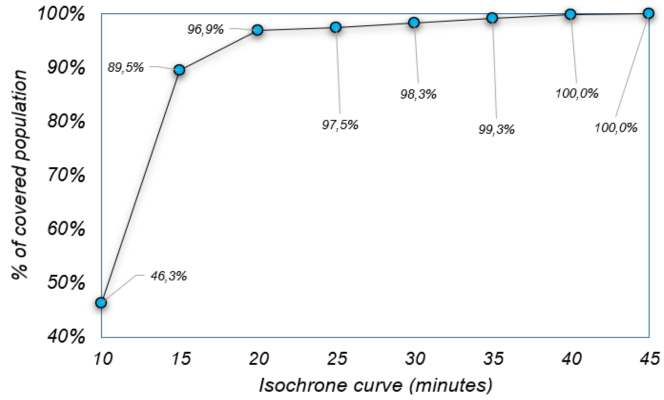

Figure 6. Ogive percentage of cumulative coverage. Mode of transport: bicycle (Source: authors)

Result 3 – Accessibility conditions for the public transport mode (Figure 7). The urban public transport proposal consists of two terminals (bus stops) located in La Paz (North) and Comuneros (South) neighborhoods (Alcaldía de San José del Guaviare, 2002), and six (6) routes designed to meet the demand between the residential sectors and the sectors where the primary activity nodes are located.

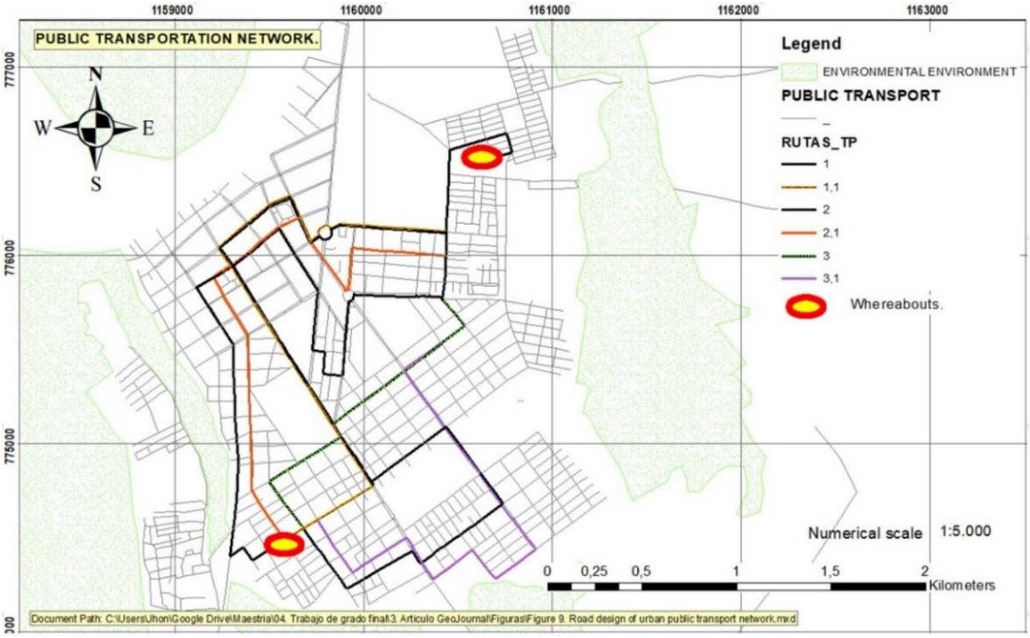

Figure 7. Proposed public transport routes (Source: authors)

The assumed operating speed for public transport in this study is 30 km/h, derived from operational data in cities like Manizales (29 km/h) and Popayán (31 km/h) with comparable characteristics (Montoya, 2019; Escobar, 2008).

The overall average accessibility for this mode, illustrated in Figure 8, reveals a 10-minute isochronous curve covering 70% of the population (29,296 inhabitants), followed by a 15-minute curve reaching 92% (33,244 inhabitants). These curves encompass the majority, and it's worth noting that all planned routes operate within or below a 10-minute average travel time. Future public transport route extensions should align with existing and potential urban expansion areas for sustainable municipal growth. Territorial accessibility proposals for the public transport network, outlined by neighborhood boundaries, indicate broad coverage within the main urban polygon but with limitations in expansion zones.

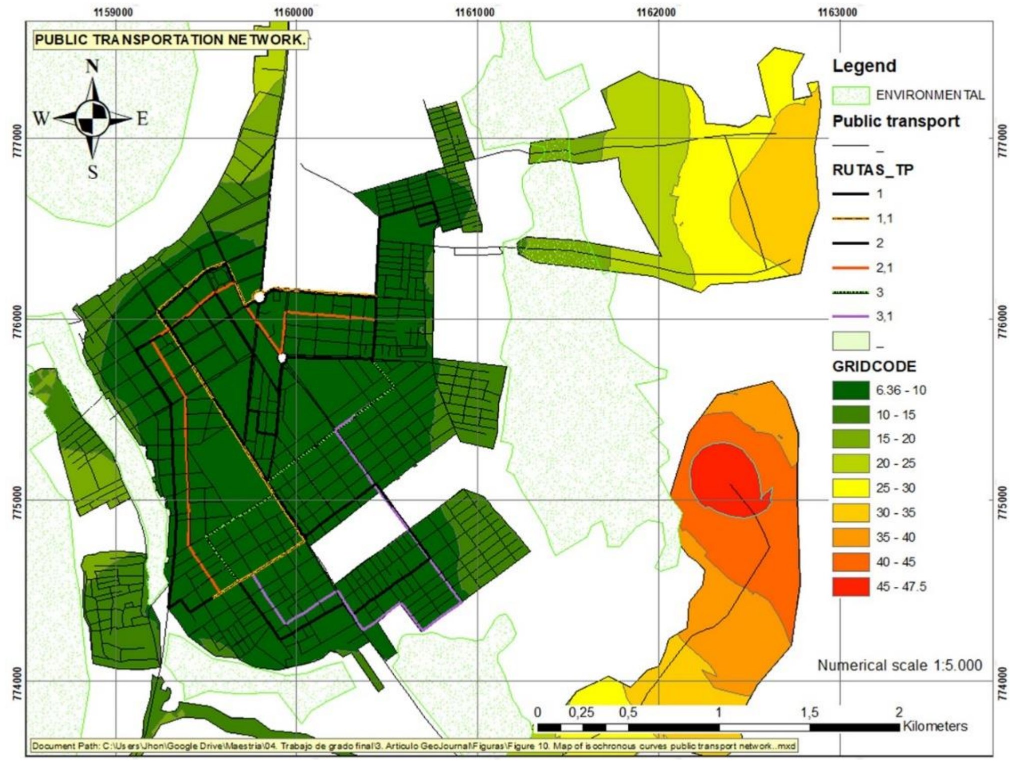

Figure 8. Overall average accessibility conditions. Transport mode: public (Source: authors)

Figure 9 displays the cumulative population coverage, showing almost 70% covered within a 10-minute travel time, encouraging the integration of active transport modes (walking and cycling). The goal is to promote environmentally friendly transportation, especially in an area requiring environmental protection.

The average travel time for public transport was found to be 12.5 minutes, one minute less than the bicycle mode of transport, which clearly establishes that there are high possibilities for the success of this type of transport mode, as long as they are articulated and their service is provided in a comfortable, safe and economically accessible way for the population, as bicycle use would be free, which would be an important advantage itself.

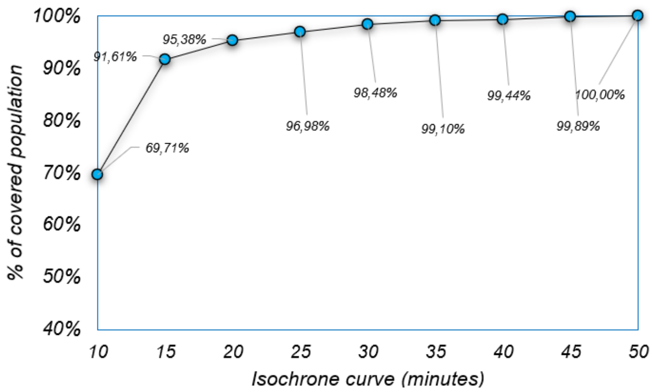

Figure 9. Ogive percentage of cumulative coverage. Transport mode: public (Source: authors)

Result 4 – Accessibility conditions for the private mode of transport: Firstly, the process of calculating the operational conditions for this mode of transport is described, which, as a special feature, is the only one that is currently considered in land-use plans, making this the first research study to involve and propose the inclusion of sustainable modes of transport in this municipality. To calculate the operational speeds, the information reported by Google Maps about the average travel time on each arc was used to calibrate the network for the appropriate adjustment of the transport supply model. A total of 182 arches in the urban area and 32 arches in the urban expansion zones were evaluated, for a total of 214 arches. The travel time results for the arches obtained using the Google Maps tool implicitly contain all turning times and other time loss events caused by any technical or social reason that affects mobility; therefore, no turning penalties will be considered in the development of the calculations. Table 1 shows the minimum travel-time calibration results for thirty random routes, calculated using Google Maps and TransCAD. Given the private-transport-mode network features of the current scenario, the values obtained for the arcs indicate that the average is equal to 18.28 km/h, with a range from 9 km/h to 39 km/h. Now, with the obtained data for the minimum travel time calculation, descriptive statistics and linear regression analysis are carried out to check the effective relationship of this variable and ensure the data calibration. These data are given in Table 2, which shows that as a linear regression analysis result carried out for the thirty (30) routes evaluated, it was possible to verify the high linear relationship of the values studied, bearing in mind the value of the coefficient of determination R^2, which makes it possible to infer an effective quality of adjustment.

Table 1. Calculation of minimum travel times in minutes for route analysis and comparison between TransCAD and Google Maps (Source: authors)

Ruta	**TransCAD**	**Google Maps**	**Ruta**	**TransCAD**	**Google Maps**
1	8.0072	8.00	16	7.7944	8.00
2	6.1285	6.00	17	4.9717	5.00
3	6.1180	6.00	18	4.9193	5.00
4	4.0413	4.00	19	4.1006	4.00
5	6.9419	7.00	20	4.9812	5.00
6	7.0628	7.00	21	8.9504	9.00
7	5.9991	6.00	22	5.063	5.00
8	4.2094	4.00	23	4.0187	4.00
9	6.1949	6.00	24	4.0252	4.00
10	4.8593	5.00	25	5.0172	5.00
11	3.9372	4.00	26	7.1283	7.00
12	5.0280	5.00	27	7.0883	7.00
13	6.9879	7.00	28	5.0389	5.00
14	6.0267	6.00	29	5.9712	6.00
15	4.8708	5.00	30	6.1481	6.00

Table 2. Summary of regression statistics (Source: authors)

NAME	**VALUE**
Multiple Correlation Coefficient	0.9974
Coefficient of Determination R^2	0.9949
R^2 Adjusted	0.9947
Typical Error	0.09725
Observations	30

The above means that the network model elaborated in TransCAD through the development described in the methodology is configured in such a way that it can serve as a basis for developing the global accessibility calculations in the current scenario, proposed scenarios with addition and/or modification of the existing road infrastructure, and scenarios according to transport modes. This will allow in this particular case of private mode to calculate the global average accessibility gradient.

The overall average accessibility conditions for the private transport mode in the current scenario show that the main urban polygon is covered by average travel time curves of between 5 and 10 minutes, while the urban expansion areas located to the east of the municipality are covered by travel times of up to 16 minutes (Figure 10). Figure 11 shows the aggregate coverage percentage ogive for the population variable, where it is possible to observe that a little more than 10% of the population is covered with 5-minute average travel times, and almost 99% is covered with 10-minute average travel times. Figure 12 shows the six proposed infrastructural interventions related to the private transport mode, which are intended to complement the external perimeter ring (interventions 1 and 2) and internal articulation of the network (interventions 3 - 6).

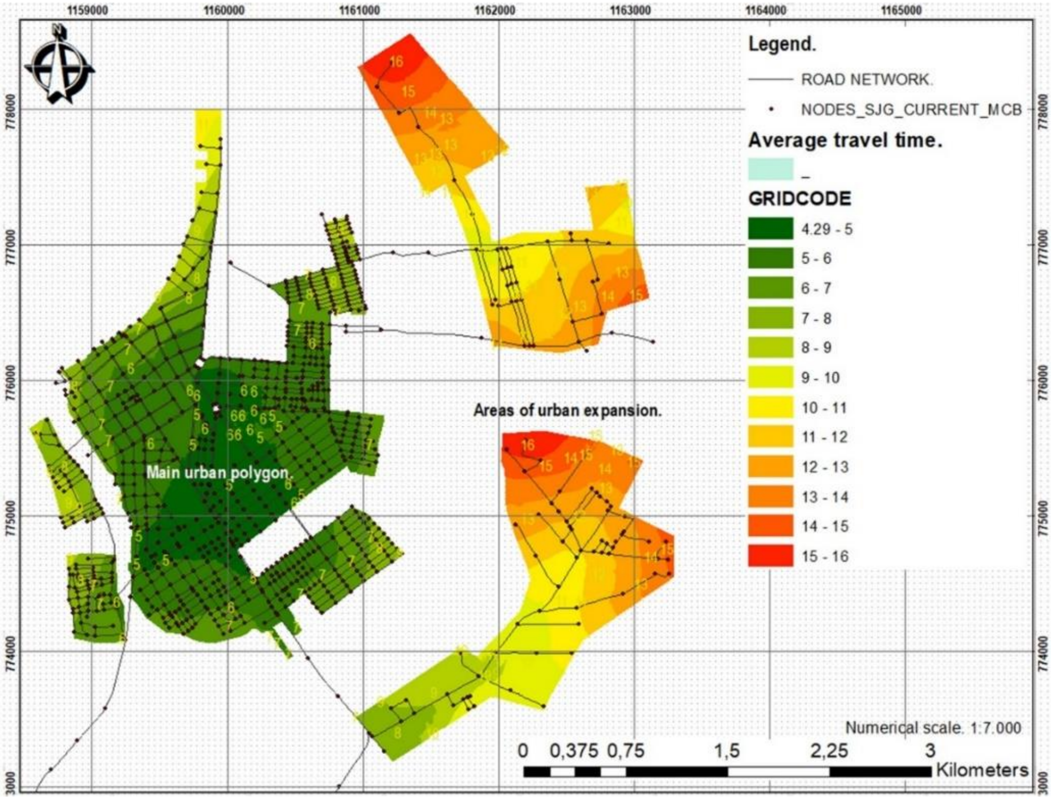

Figure 10. Overall average accessibility conditions. Transport mode: private. Current scenario (Source: authors)

Figure 13 shows the impact that the six proposed infrastructure interventions would have in terms of percentage savings in average travel times. It is highlighted that given these proposed interventions, it is the east of the city that would benefit the most from their construction, finding that the CBD continues to have the same accessibility conditions with or without the proposed interventions for this private mode. Likewise, when calculating the average travel time weighted by population, this mode of transport registers 6.6 minutes, a value much lower than that registered by the other modes of transport.

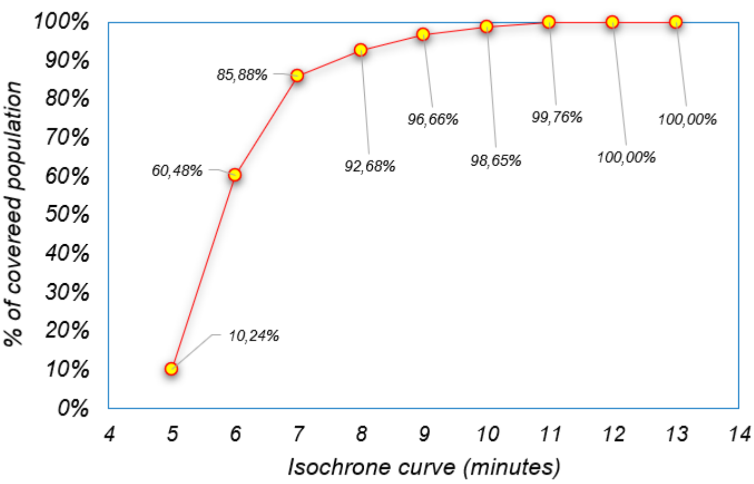

Figure 11. Ogive percentage of cumulative coverage. Transport mode: private (Source: authors)

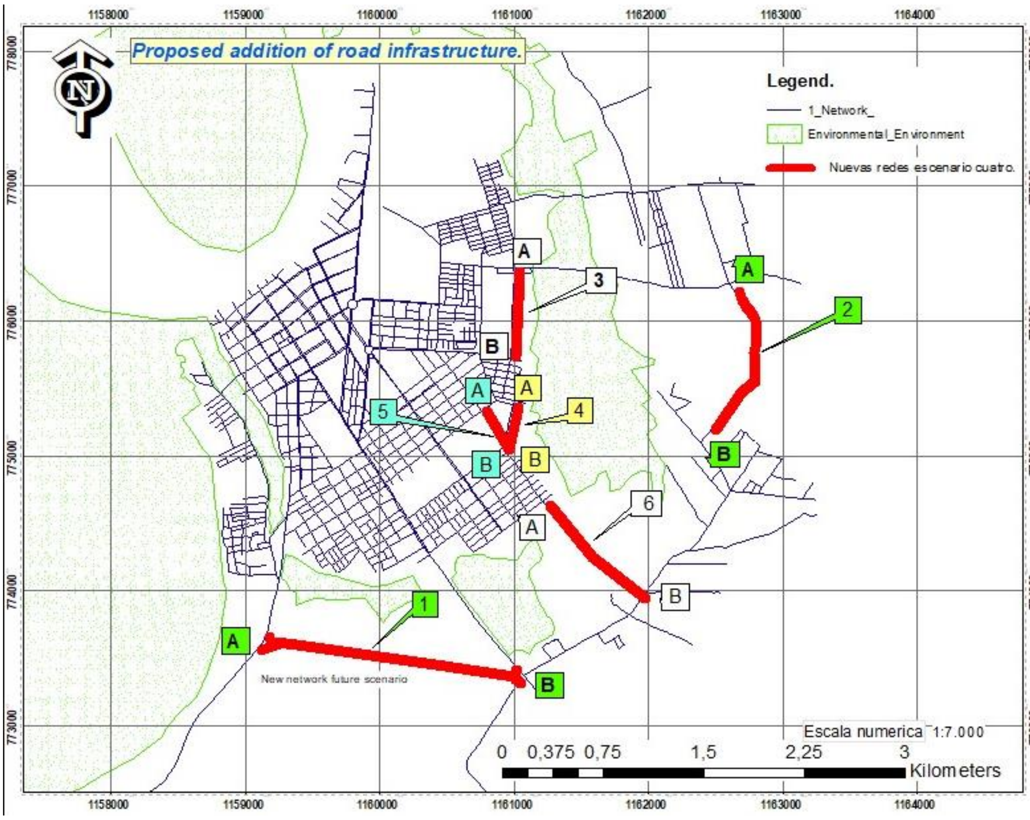

Figure 12. Proposals for infrastructural intervention in private mode (Source: authors)

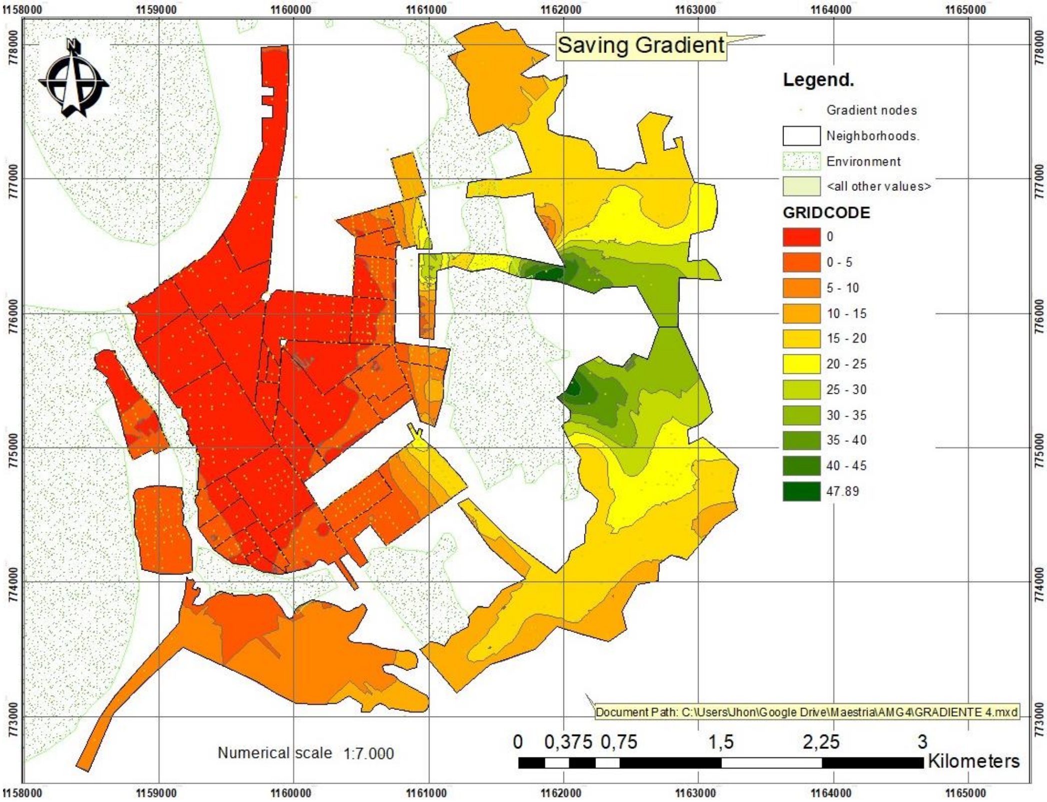

Figure 13. Private mode savings gradient (Source: authors)

CONCLUSION

The developed methodology satisfactorily calculates territorial accessibility in areas lacking transportation network information. In digitizing geographic information layers, using base maps in ArcMap proved the fastest and most effective method. For road network connectivity validation, ArcMap's Topology function was determined as the best tool. Operational speeds of road arcs were obtained through Google Maps. Regarding the network calibration, it was concluded that the simulation process of the data loaded in TransCAD does not require estimation of penalties for turns, as these time additions due to delays, traffic jams, and other time loss events affecting mobility are implicit in the operational speeds taken from Google Maps. In the analysis of global average accessibility, the existing network has a main urban polygon and distant urban expansion zones, with isochronous curves covering different time intervals.

For the analysis of new infrastructure, there are better results of territorial accessibility with a reduction of the isochronous curve from sixteen to thirteen minutes. The 8-minute isochronous curve covers 92.68% of the population, emphasizing the need for new road sections for planned expansion.

In alternative transport mode analysis, for the pedestrian network, territorial accessibility is mainly achieved in the main urban polygon under the 20-minute isochronous curve. In relation to the entire network, the coverage of the 25-minute isochronous curve is sufficient to cover a significant percentage of the population. In the scenario of the bike path network, different isochronous curves cover varying percentages of the area and total urban population.

Regarding the analysis of the scenario with the urban public transport network, favorable results were obtained, with isochronous curves covering a large portion of the population; comparing modes of transport, sustainable transport emerges as the most advantageous. It is essential to note that this research is the first of its kind in San José del Guaviare, emphasizing the town's topography for environmentally friendly transport.

Author Contributions: Conceptualization, J.J.R and C.A.M.; methodology, D.A.E. and C.A.M.; software, D.A.E. and J.J.R.; validation, C.A.M. and J.J.R.; formal analysis, C.A.M. and J.J.R.; investigation, D.A.E. and C.A.M.; data curation, C.A.M. and J.J.R.; writing - original draft preparation, J.J.R. and D.A.E.; writing - review and editing, C.A.M. and J.J.R.; visualization, J.J.R. and C.A.M.; supervision, D.A.E.; project administration, C.A.M. 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 researchers would like to thank the Universidad Nacional de Colombia and the members of the Sustainable Mobility Research Group (GIMS) - especially the engineer Santiago Cardona. External academic peers assigned by the journal, to whom we are grateful for their comments and suggestions, reviewed this article.

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

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Article history: Received: 02.02.2024 Revised: 12.04.2024 Accepted: 08.05.2024 Available online: 30.05.2024